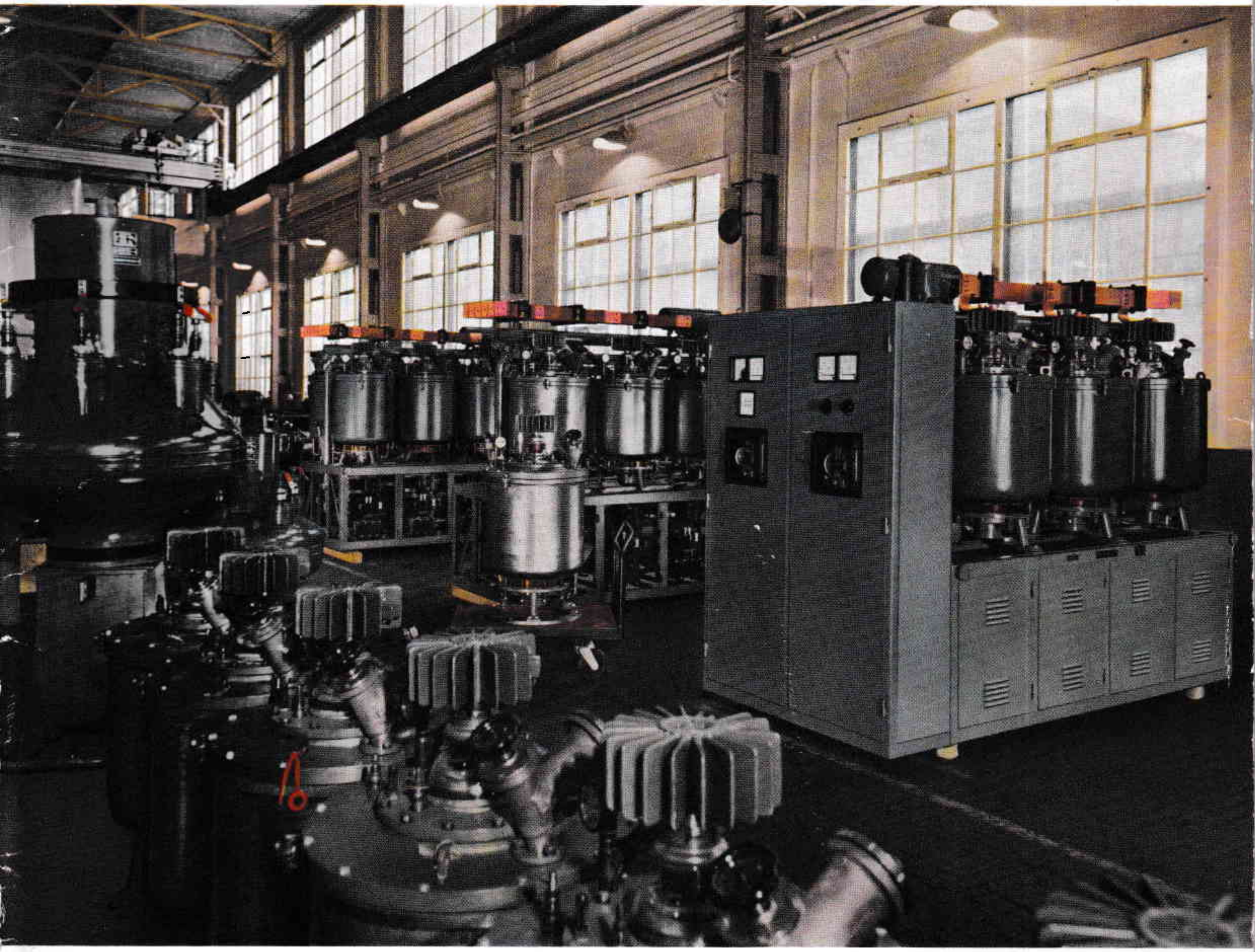
THE

BROWN BOVERI REVIEW

Mutators



Section of the Brown Boveri mutator factory

Right: 5000-A, 750-V mutator sets each comprising six single-anode tanks. Left: Air-cooled six-anode mutator rated 930 kW at 750 V or 2000 kW at 3600 V. In the left-hand foreground various mutator tanks are also visible.

BROWN BOVERI REV. VOL. 42 No. 4/5 p. 117-184 BADEN, APRIL/MAY 1955

Printed in Switzerland

THE BROWN BOVERI REVIEW

ISSUED BY BROWN, BOVERI & COMPANY, LIMITED, BADEN (SWITZERLAND)

VOL. 42 APRIL/MAY 1955 No. 4/5

CONTENTS:

INTRODUCTION

ALTHOUGH Brown Boveri are certainly entitled to look back with pride on their share in the development of the mutator, they prefer to devote their whole attention to the present and future and consider those aspects of electrical engineering where there appears to be a demand for direct current, enumerating here the wide variety of means which they have to offer for converting alternating to direct current.

Soon after the war it became obvious that the six years of complete isolation from the rest of the world had left us with an exaggerated opinion of the merits of direct current for long-distance transmission. In the meantime, however, alternating current had been able to improve its economic position: now the arrival on the scene of atomic energy has brought with it a completely new conception of the economics of energy production. Nevertheless, the traditional spheres of d.c. application, i.e. industrial drives—with regard to which the Company's interests lie not only in the provision of the driving equipment but also in its control — electrochemical electrolysis and electric traction, have regained their full significance for this type of current.

Recognition of these facts compelled the Company to revise their views regarding the most suitable design for mutators, as distinct from rotating converters, which will not be dealt with here. For instance, a complete change-over has been made to air cooling for mercury-arc mutators, with the exception of one heavy-current type where water cooling has been retained, as this method seemed most appropriate for large electrolysis plants. In addition, single-anode designs have been produced, possessing both economic and technical advantages, although the medium- and low-power six-anode types are simpler to install. Progress in vacuum physics has now made it possible for the latter type to be constructed in the pumpless form and, furthermore, for an enclosed, air-cooled, single-anode mutator to be developed, which combines all the features demanded by service in single-phase mutator locomotives.

In this general review, mention must also be made of an important development from mercury-arc mutators, hot-cathode electronic tubes called diodes or, in a more complicated form, thyratrons. The standardized range of Brown Boveri tubes can be employed in the solution of all control problems, as well as in rectifiers for all kinds of high-frequency transmitting and generating equipment.

At the same time, however, the mechanical contact converter has been developed into a completely reliable piece of industrial equipment. Its high efficiency at heavy currents is enabling it to oust the mercury-arc mutator from an increasing number of electrolysis plants, where it fulfils all the requirements of the electrochemist in respect of choice of voltage.

And now, as if the list of rectifier types were too short, there appears another constellation, though still only a faint glimmer on the horizon, the semi-conductors. There seems to be no reason why this new discovery should not conquer the very-heavy current field at low voltages. It is sufficient for the present, however, to say that Brown Boveri will certainly not let it escape their attention.

P. Waldvogel (KME)

THE PROBLEM OF PRODUCING DIRECT CURRENT

621.314.6

After briefly mentioning the various applications of direct current, the author proceeds to describe the characteristics of the different types of converter now available, devoting particular attention to single- and multi-anode mutators and contact converters as developed by Brown Boveri.

The Utilization of Direct Current

WHEREAS in the early days of electrical engineering direct current played a predominant part in almost every sphere of application of electricity, as years went by its significance tended to become restricted to a few interesting specialized fields such as traction, electrochemistry, heavy industrial drives and most recently atomic research (for cyclotrons, synchrotrons).

Before dealing in greater detail with the types of converter in use today, a brief summary will be given of the main fields in which direct current is employed.

1. The use of d.c. in town supply networks, which was quite common in the early days, is now decreasing in popularity. Existing electrical installations are not being extended and their importance is continually diminishing.

2. In the field of traction, the mutator is playing a leading part in the supply of energy to tramways and main-line and local railways. The excellent properties of the robust d.c. traction motor will enable this field to continue to develop in future alongside the various a.c. systems.

3. In heavy industry, particularly in steel works and mines, the value of d.c. for variable-speed drives, where accuracy of regulation is all-important, is receiving increasing recognition. Here the desired precision and speed of response can in many cases only be obtained with the d.c. motor in conjunction with either the grid-controlled rectifier or the Ward-Leonard converter. With modern means of regulation the speed of a motor can be controlled to an accuracy of 0·1 per cent. Moreover, the grid-controlled mutator allows the speed of d.c. motors to be regulated accurately over a very wide range, if necessary down to rest.

4. The principal field of application of direct current is in the plants of the electrochemical industry engaged in the electrolysis of aqueous solutions and fused salts, where currents of 100 kA and above are encountered, at voltages ranging from a few volts up to 1 kV or more. Since for these gigantic energy consumers the price of the final product is closely governed by the efficiency of the electrolytic process, the converter efficiency is a preponderant factor in determining which type of converter shall be used for a particular duty (Fig. 1).

The Main Types of Converter

D.C. is either generated as such or obtained through a converter. The first method, using d.c. generators, is obsolescent because the most economical generator output is limited to about 6 MW by the low terminal voltages, while the transmission of the energy over long distances is not a paying proposition. Extensive electrochemical plants

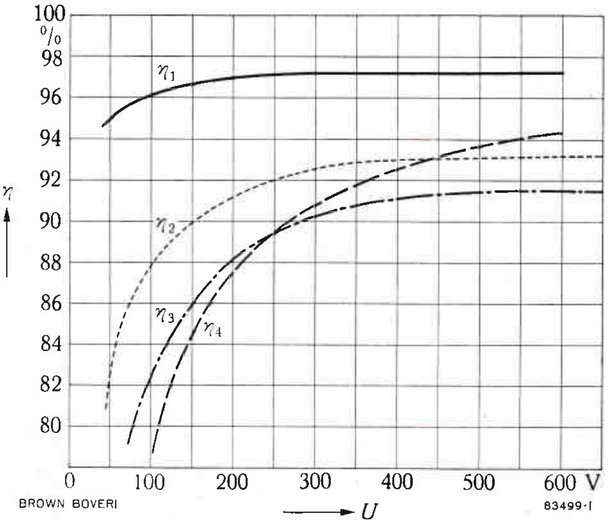


Fig. 1. — Comparison of overall efficiency η of various types of converter in relation to the d.c. voltage U

η_1 = Efficiency of contact converter including transformer, anode reactor and all auxiliaries
η_2 = Efficiency of rotary converter
η_3 = Efficiency of motor-generator
η_4 = Efficiency of mutator including transformer and all auxiliaries

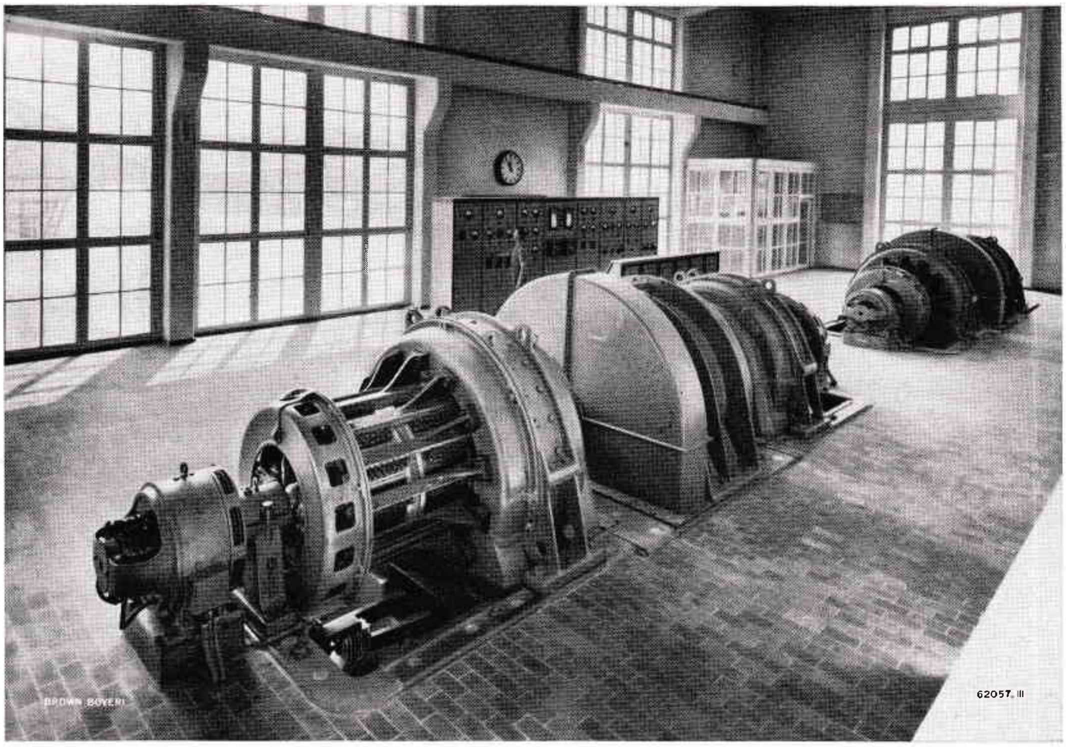


Fig. 2. — Converter substation in a chemical works

The two motor-generators, each rated 2×7·5 kA at a d.c. voltage variable between 30 and 100 V, supply energy to an electrolysis plant. In the background are the switchgear and controls.

would require an undesirably large number of parallel-operating generators involving very large capital investments; even then such a scheme would only be possible if local conditions permitted the equipment generating and consuming the power to be installed within close proximity of each other. Owing to these disadvantages practically only the indirect method of d.c. generation, i.e. via converters, is now given consideration for large installations.

Motor-Generators

The motor-generator (Fig. 2)—with whose method of operation it is assumed the reader will be familiar—is now used only in exceptional cases in new high-powered installations. The double conversion from a.c. electrical into mechanical and from mechanical into d.c. electrical energy cannot but result in heavy converter losses, and overall efficiency figures of, at the most, 92% are to be expected. However, this converter set possesses one particularly valuable feature in that the d.c. voltage can be regulated with ease between 0 and 100%.

Rotary (Synchronous) Converters

As the rotary converter changes a.c. to d.c. in a single machine, the losses are naturally much lower than in the motor-generator. The design as a single-armature machine, however, demands that the a.c. and d.c. voltages should be roughly of the same magnitude; therefore for equalization of the one to the other, it is often necessary to provide an additional transformer. Moreover, a reasonably large range of voltage regulation is only possible by superimposing a variable a.c. voltage or connecting a choke in series. Commutation, particularly when the operation involves spasmodic surges and short circuits (e.g. traction), presents a difficult problem. As a result of these disadvantages, interest in the rotary converter today is practically nil.

Mutators

After publication of the main patents, the mercury-arc mutator did not progress beyond the status of a laboratory apparatus for many years; in fact, it was not until the manufacturing rights were acquired by Brown Boveri that an

unprecedented development period commenced, initially for railway application, where the following features contributed to the success of the mutator:

- No rotating parts
- Low weight
- Hardly any foundations required
- Direct conversion without intermediate mechanical stage
- Consequent higher efficiency, also on partial loads
- Imperceptible wear in operation
- Low maintenance costs
- Long life

The introduction of the controlled anode grid permitted rapid, loss-free and infinitely variable regulation of the d.c. voltage between certain limits; furthermore, with the help of the control grid the development of an extremely effective means of protection against internal short circuits became possible.

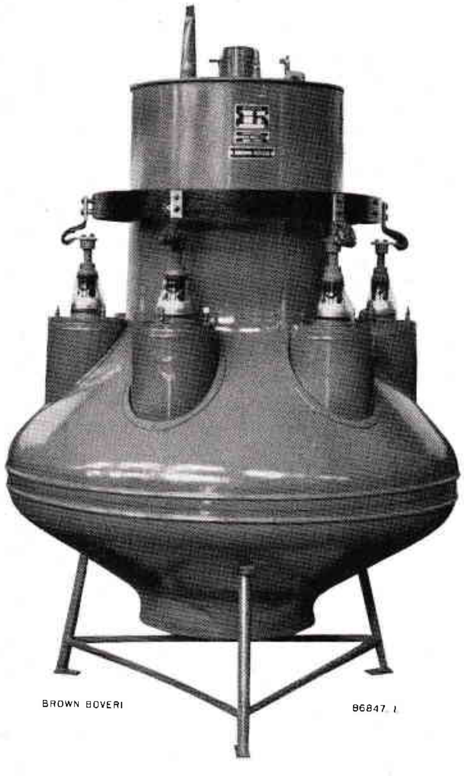


Fig. 3. — Pumpless, air-cooled, grid-controlled, six-anode mutator rated 2 MW at 3·6 kV or 960 kW at 800 V

The simple design of this type of mutator renders it particularly suitable for automatic and remote-controlled traction substations. The grid also protects the mutator against short circuits and back-fires besides acting as a means of voltage regulation.

With the exception of certain electrolytic processes, which use very heavy currents at extraordinarily low voltages, the mutator, in one form or another, can be recommended as the most economical method of conversion for all large consumers of direct current. The selection of one particular type of mutator for a given application is governed primarily by the capital charges, maintenance costs and efficiency of conversion. Backed by the experience gained in forty years construction of mutators, and the development work carried out over this period, Brown Boveri are in a position to fulfil all their customers' requirements, and to offer the most appropriate mutator for every duty. For small and medium railway installations where initial costs play a particularly important part, the simple, air-cooled, multi-anode, *pumpless*, steel-tank mutator—which is also eminently suitable for automatic installations—has all but superseded the glass-bulb and water-cooled, pumped, steel-tank types. To avoid overvoltages due to low external temperatures this type of mutator is injected with a small quantity of inert gas, in addition to which the anodes can be heated to prevent the condensation of mercury on them.

For large substations several pumpless mutators can be connected to a common transformer to give combined outputs of 2–3 MW, depending on the desired d.c. voltage. This, in one way, advantageous connection of several mutator tanks to one transformer nevertheless requires a multiplicity of auxiliaries and controls with the associated leads between the individual sections of the installation. In such cases, therefore, it may be more appropriate and cheaper to utilize the larger air-cooled multi-anode mutator with vacuum pump set. This type of mutator, which is less sensitive to operational overloads, is capable of outputs up to 3 MW at 3·6 kV from a single unit (see Fig. 10 on p. 131). It is therefore particularly well suited to main-line traction or for supplying reversing or continuous rolling mill drives and the like.

In large installations, especially for the electrolysis of aqueous solutions or fused salts, where the voltage exceeds 400 V, the time-proved, water-cooled, twelve- and eighteen-anode mutator is being increasingly superseded by the single-anode steel-tank type with vacuum pump and water cooling. Whereas in the USA the production of the single-anode (Ignitron) type, ignited and controlled by an ignitor,

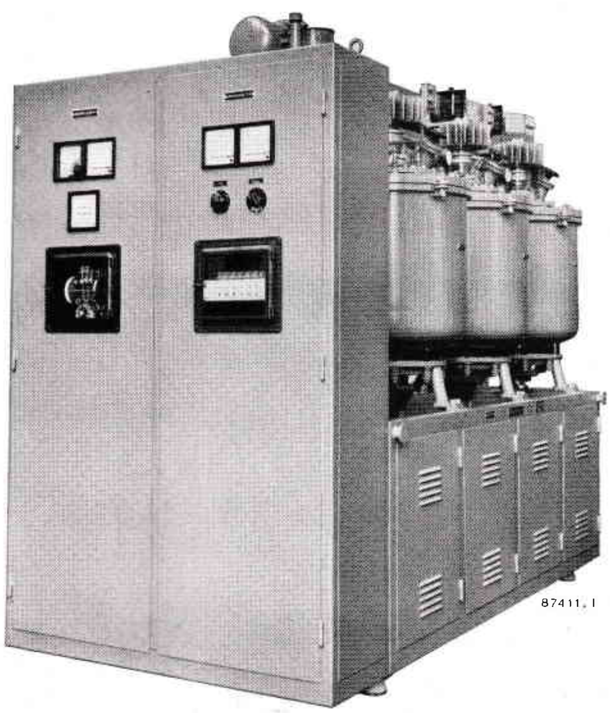


Fig. 4. — Mutator set 5 kA at 750 V consisting of six water-cooled single-anode tanks

This single-anode type was specially developed for use in electrolytic plants where working voltages may be up to 1000 V or above. A special design without vacuum pump and cooled by air is also intended for direct erection in locomotives.

is predominant, Brown Boveri transferred the well-tried principle of permanent excitation, as used in the multi-anode mutator, to single-anode tanks (Excitrons). Corresponding to the single or multiple six-phase connection of the transformers, the single-anode tanks are combined in groups of six (Fig. 4), each group being joined to a common vacuum pump set. In this way combinations of up to 24 tanks supplied by one transformer can provide a continuous current of 12 kA. The advantages of the single-anode tank are as follows:

- Lower arc-drop
- Easy replacement of a faulty tank
- Low storage costs and the ability to use circuits with different cathode potentials, which is of particular value in high-voltage installations.

As single-anode mutators are mainly employed in the chemical or metallurgical industries, where a slight increase in water consumption is hardly noticeable and the layout of a group of six tanks can be appreciably simplified by the omission of the fans and their controls, there is a distinct preference for water as a means of dissipating the heat developed in single-anode tanks. For special applications, such as mutator locomotives, which are fed from the 50-c/s supply system, single-anode mutators have also been developed with air cooling. Below each mutator tank is a fan which forces air between the outer sheet steel casing and the fins welded on the tank. In order that the layout of equipment on the vehicle may be as simple as possible, single-anode tanks have recently been developed which require no vacuum pump.

Contact Converters

The mutator, in its various modern forms, can still be considered the most economical a.c.-d.c. converter for the majority of the applications listed on p. 120. Nevertheless, a relatively wide electrochemical field is gaining in importance, where the use of mutators is hardly to be recommended for economic reasons; this covers the various electrolytic processes using heavy currents of 20–100 kA at low voltages from 50–300 V. Formerly for this purpose there were developed, for example, the so-called unipolar machines, but the associated current-collection problems were never really satisfactorily solved. This gap is now filled by the contact converter (Fig. 5), a mechanical rectifier, which allows an overall efficiency of 95% at 100 V and 97% at 300 V, inclusive of all transformer and choke losses, to be guaranteed. A simple calculation shows that the energy saved by a low-voltage contact converter installation covers the capital outlay of a new installation inside ten years. The fact that such high efficiencies are obtained, even at low voltages, is easily explained by the absence of arc-drop. In a contact converter the a.c. is changed into d.c. by the carefully controlled action of the metallic contacts, the losses at the breaks being practically negligible compared with the arc losses in a mutator. Further details of the construction, mode of operation and special circuit problems of the contact converter are to be found in a special number of this journal.[1]

Many years' operational experience and the large number of installations completed or under construction confirm

[1] Brown Boveri Rev. 1950, Vol. 37, No. 12.

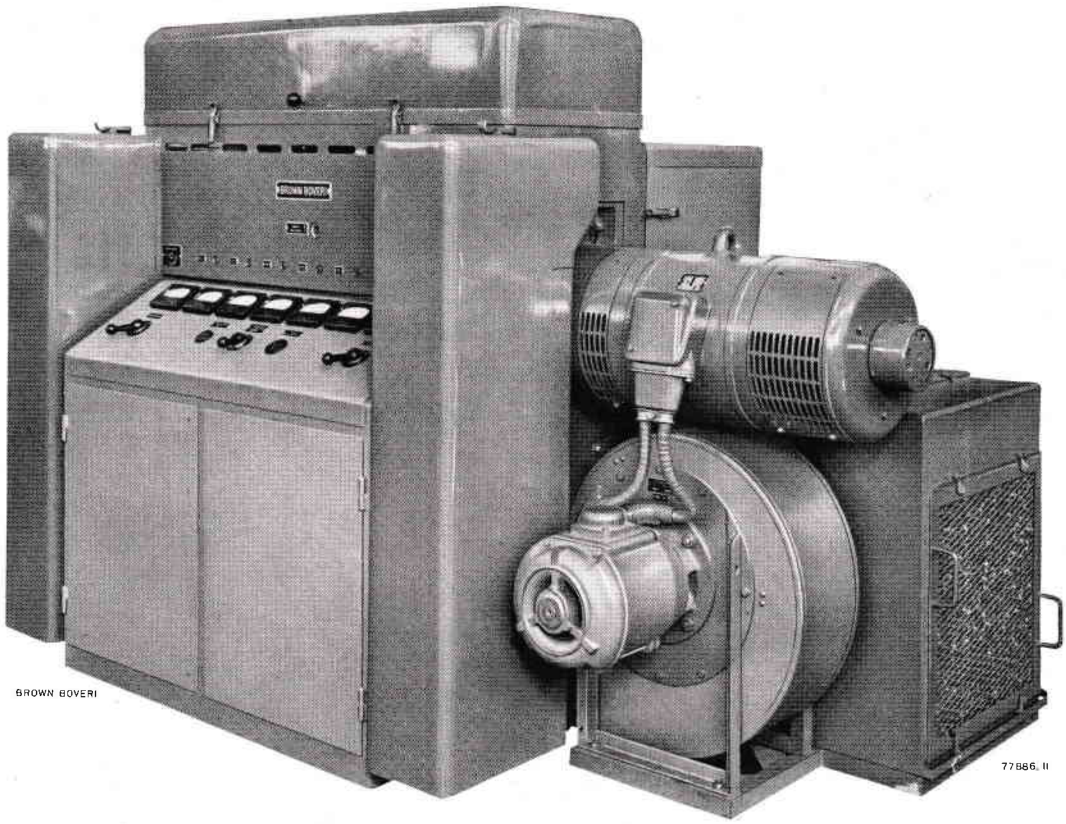


Fig. 5. — Contact converter set with built-in control desk and built-on centrifugal fan

The output of this converter is 5 MW at a d.c. voltage between 200 and 500 V. Due to its excellent efficiency it is particularly suitable for heavy-current duties at low to medium furnace or electrolysis voltages.

that Brown Boveri can supply contact conversion plant capable of meeting all the demands of continuous day and night operation in metallurgical and chemical works, and that over the years a degree of reliability is achieved quite equal to that of mutators or rotating electrical converters.

As a result of extensive, systematic research and the considerable experience gained from several years industrial operation, Brown Boveri can now confidently supply contact converters, guaranteed for the following operating conditions:

10 kA at a maximum of 500 V

20 kA at a maximum of 250 V

25 kA at a maximum of 200 V

To make matters quite clear it is emphasized that the contact converter, due to its high efficiency even at low voltages, is considered suitable principally for use in chemical and metallurgical works.

The foregoing notes demonstrate that Brown Boveri are now in a position to supply equipment, which besides being most economical, is operationally best suited to the requirements of all direct-current consumers.

MS 820 (KME) *M. Rossé*

DEVELOPMENT OF THE BROWN BOVERI MUTATOR

621.314.65

After reviewing the various stages of evolution traversed by the mutator since its inception, the author describes designs, properties and uses of modern mutators, in the development of which Brown Boveri are playing a leading part.

OVER forty years have elapsed since Brown Boveri commenced manufacture of metal-tank mercury-arc mutators, being the first European company to enter this field. Here, too, as is so often the case when a scientific principle finds a technical application, success was not due directly to the basic idea, but to the manner in which the problem was tackled. Actually, the successful combination of solutions to a number of detail problems permitted a static apparatus to be designed for the conversion of alternating into direct current. In the meantime the mutator has found its way into all branches of engineering and, throughout the considerable progress achieved in its development has always kept pace with, and in some respects, even outstripped technical requirements.

Earlier Developments

When mutator development first began in Europe, only relatively low-current types were made (Fig. 1). Not until the early 1920s, when the results of research became available and the weaknesses of the original designs had been recognized, was it possible to introduce batch production of mutators with increased output and higher d.c. voltages. On account of the increasing diameter of the tanks, as well as for other reasons, acetylene—which until then had always been used to weld them—had to be discarded in favour of electric welding. This latter system was, however, at that time still in its infancy, and this fact alone demanded the accumulation of a great deal of practical experience before tanks could be made which were really sound and vacuum-tight.

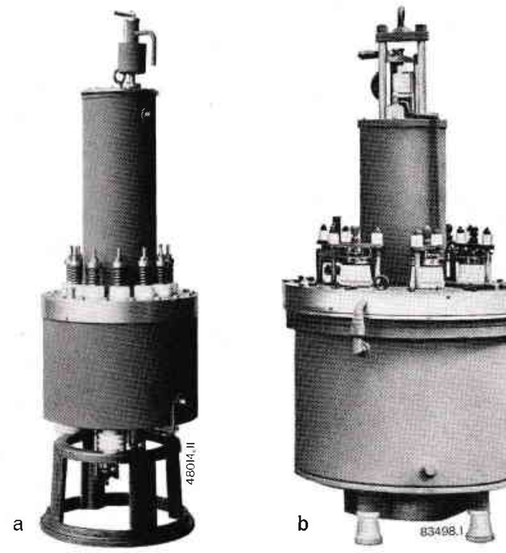


Fig. 1. — Early examples of Brown Boveri mutators: Water-cooled steel-tank designs

(a) Year of construction 1913, rating 150 A
(b) Year of construction 1915, rating 250 A

Brown Boveri were the first concern to develop grid control for voltage regulation and the suppression of short circuits and back-fires, this being towards the end of the 1920s. The general introduction of this feature into mutator design inaugurated a new development stage during which, above all, the construction of internal components underwent a fundamental change. The shape of the ceramic parts, the anodes, grids and shields had to be adapted to the new conditions, both mechanically and thermally. Certain new materials also had to be found on account of the high temperatures.[1]

It goes without saying that the development of the mutator was accompanied by that of the accessories; this will be passed over here though, as it has been adequately described in the past (see p. 180 of this issue). Only the subject of cooling will be touched upon, as throughout the entire development period the method of cooling has had a considerable effect on the design of mutators and their accessories.

For the first twenty years all steel-tank mutators had water cooling to dissipate the heat generated; in most installations the cooling water was taken straight from the supply mains. In the course of time, however, this method fell into disfavour as the pipes became corroded to a greater or lesser degree, according to the properties of the available cooling water. Moreover, the importance of uniform heating of the tank soon became evident, which led to the exclusive adoption of recirculation cooling with the resultant freedom from corrosion and simpler temperature regulation.

There are two methods by which mutators can be water cooled depending on the amount of water available:

[1] Brown Boveri Rev. 1938, Vol. 25, No. 5/6, p. 83–93.

Fig. 2. — Steel-tank low-power mutator with forced air cooling
Year of construction 1935, rating 400 A

1. *Water-cooled recirculated cooling water.* – In this process an impeller pump forces the water through a counterflow heat exchanger, which itself is cooled by fresh water. The temperature of the circulating water and therefore of the mutator is maintained practically constant by a thermo-regulator consisting of a thermostat and a regulator valve, which automatically governs the rate of water consumption according to the mutator load. This method is mainly used for installations with a high current rating.

2. *Air-cooled recirculated cooling water.* – This method is used mostly where water is either unavailable or expensive. Temperature control is simple, a thermostat on the mutator tank opening or closing the fan switch.

The first mutator, in the classic glass envelope as devised by Cooper-Hewitt, appeared some fifty years ago; the heat developed was dissipated simply by convection. Soon, however, notable progress was made in the construction of glass bulbs, particularly in respect of glass technology, which permitted higher currents and brought about the introduction of artificial methods of cooling.

At the outset, solely water-cooled steel-tank mutators appeared in the Brown Boveri production schedule, and it was not until the early 1930s that a low-power mutator (400 A at 600 V) with forced-air cooling was developed (Fig. 2). This was the first time the glass-bulb type had

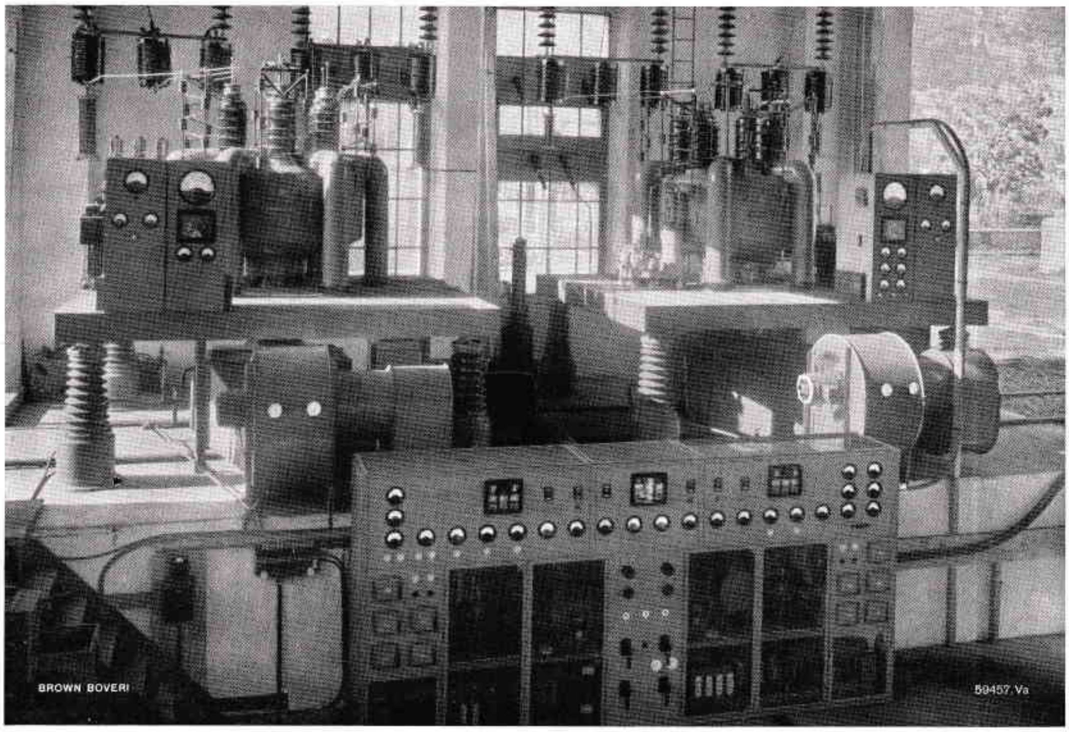


Fig. 3. — Power transmission using high-voltage d.c.: field trials in progress at power station

The two mutator sets (top) with their auxiliaries are mounted on high pedestals, insulated from earth by means of pillar insulators. Underneath are the two sets of cooling equipment. In the foreground the combined switchboard for the terminal stations of the transmission line is visible.

met with any serious competition, also in respect of the method of cooling. Here it is noteworthy that the air cooled not only the mutator but also the static pump. In the years that followed, further air-cooled mutators were batch-produced, with higher current and d.c. voltage ratings. These proved their worth not only in industry and traction, but also in radio broadcasting installations.[1]

Brown Boveri took a similar leading interest in the problem of power transmission using d.c. at very high voltages. In this respect readers are reminded of the first 50-kV d.c. transmission using mutators from Wettingen to Zurich on the occasion of the Swiss National Exhibition in 1939,[2] and of the full-scale tests carried out at Biaschina power station (Fig. 3) in 1943/4.[3]

After the various six-anode types of mutator had been re-designed for air cooling, the demand for this class of converter rose sharply, because it was no longer necessary for mutator substations to be connected to a water supply and they could therefore be situated in remote positions. So far orders have been received for over 500 air-cooled mutators of the types developed in recent years.

[1] Brown Boveri Rev. 1944, Vol. 31, No. 7, p. 215–21.
[2] Brown Boveri Rev. 1939, Vol. 26, No. 4/5, p. 92–6.
[3] Brown Boveri Rev. 1945, Vol. 32, No. 9, p. 284–95, 310–21.

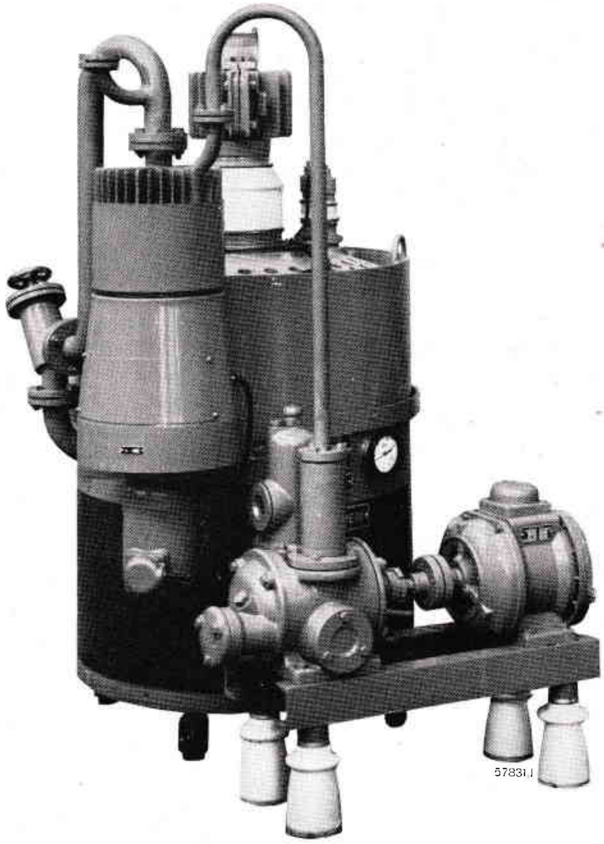


Fig. 5. — Air-cooled single-anode mutator with built-on pumping set for use in a special high-voltage circuit

A 7-MW group consisting of several such units operates at 8-12 kV d.c.

Fig. 4. — Single-anode mutator air-cooled by a propeller-type fan

Mutators of this type are banked, usually in groups of six, and connected to a common pumping set. The combined output of such a group amounts to about 2 MW at 750 V.

Towards the end of the 1930s, after laboratory tests and trials with prototypes in existing installations, Brown Boveri began marketing forced air-cooled pumpless mutators. These are distinguished by their clear layout, simple control, economic operation and small space requirements, all of which are vital in service.

Since pumpless mutators came on the market the Company has supplied several hundred units to most parts of Europe and during the course of this year many more will leave the Baden works. Now that certain initial teething troubles have been overcome, operational results are excellent. Some of these mutators have now been operating for over 60 000 hours without a single disturbance.

The most recent addition to the range of Brown Boveri mutators is the single-anode type. The air-cooled mutator of this class illustrated in Fig. 4 was supplied for a low-voltage heavy-current installation; in Fig. 5 can be seen a single-anode mutator of similar design for use in a special high-voltage circuit.

Present Status of Development

From the foregoing it will have been seen that the constructional development of the mutator progressed by various, clearly defined stages. Simultaneously with this development, especially during the last twenty years, the demand for electrical energy has increased enormously, particularly for traction applications and electrolysis installations where very heavy currents are required. In the latter field especially, the heavy-current mutator with its higher efficiency has almost completely displaced rotating converters. For such heavy-current consumers only high-output installations made up of several mutators banked together can be considered. As the cost of current is an important factor in such installations, it is only natural that the converter having the smallest losses should be chosen. The standard types of mutator, having twelve or eighteen anodes, had reached a size at which arc losses could no longer be reduced without affecting reliability. Therefore the tendency was towards designs in which the current could be distributed over a number of tanks; at the same time the anode had to carry as heavy a current as possible, resulting in tanks with a small number of anodes. This led to tanks having one to six anodes.

In recent years a number of concerns both in America and in Europe have brought out new types of mutators having one, three or six anodes. In the USA in particular, during the wartime expansion of the aluminium industry, the single-anode, water-cooled, non-permanently excited mutator or Ignitron was developed and put into production. In this type the arc drop was reduced by a few volts compared with multi-anode mutators; against this, however, the rate of occurrence of back-fires rose so that screens had to be placed between anode and cathode, which again increased the arc drop. To prevent the back-fires from having any external effect, an automatically reclosing circuit-breaker had to be included in each anode lead. An additional disadvantage of the Ignitron type of mutator is the relative complexity of the ignition system, the auxiliaries of which are definitely more extensive than those of multi-anode mutators. These also bring about increased losses which almost nullify the arc drop gain. The great advantage of single-anode types compared with those having, say, twelve or eighteen anodes is the improved stand-by facilities of such installations. For instance, in the event of breakdown one tank can easily and quickly be removed and replaced by a spare unit. In addition, small arc losses can be achieved with a high degree of reliability in operation and regulation, despite the heavy anode current.

Designing such single-anode tanks becomes quite difficult because a back-fire in one tank will affect the other tanks and thus aggravate arc extinction by the grids. Thus exhaustive prototype tests at the works and under service conditions were necessary before sufficient information had been gathered to permit the design of a single-anode tank suitable for batch production.

Whether single- or multi-anode, one of the most important components of a mutator is the anode and the arrangement of its grid. In recent years, increasing demands have been made on the control of mutators for a variety of technical purposes. To improve the control and arc-extinction properties it was not sufficient merely to modify an existing design: a completely new conception of anode valve [1] was necessary. For this reason Brown Boveri recently decided, even for pumped mutators, to adopt a glass-metal seal for the entries to the main and exciter anodes and grid. The Company already have considerable experience of the manufacture of such seals,

[1] Valve in this respect refers merely to the components in direct contact with the arc, i.e. anode, anode shield, grid and cathode, see p. 133.

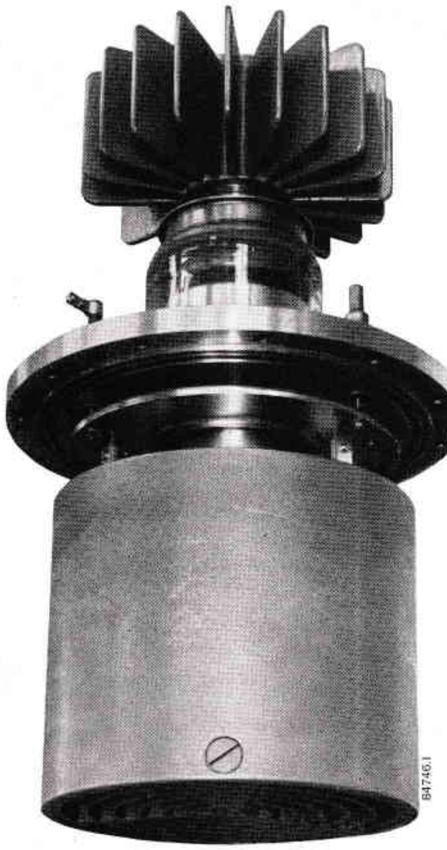


Fig. 6. — Valve construction of main anode of latest pattern with control grid

The glass fittings by which the anode and grid are fastened, are fused into the same flange. The anode itself is fastened to the lower end of a stud passing through the upper flange of the glass fitting.

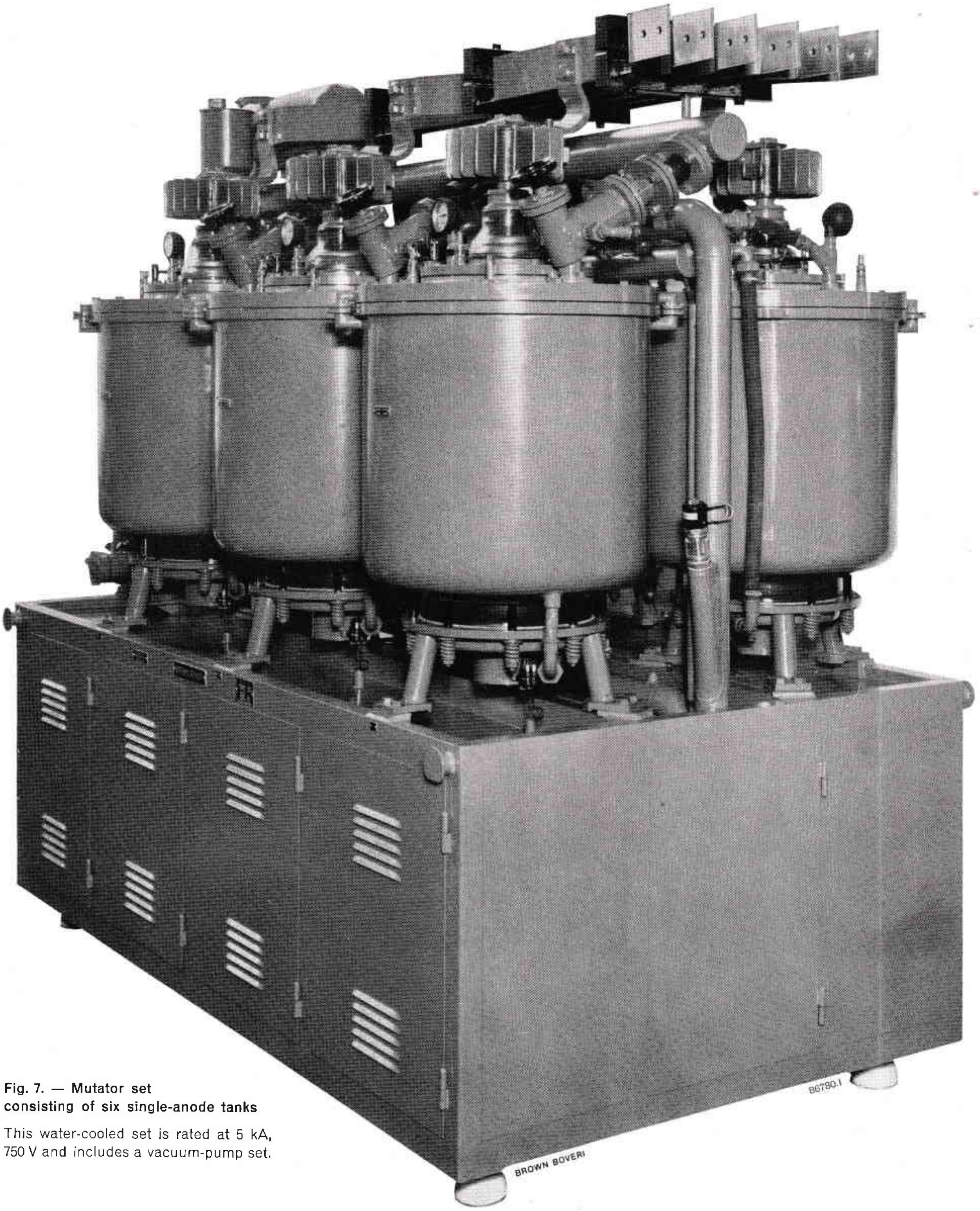


Fig. 7. — Mutator set consisting of six single-anode tanks

This water-cooled set is rated at 5 kA, 750 V and includes a vacuum-pump set.

gained from many years' production of electronic tubes.[1] A glass bushing provides good insulation; being transparent it permits inspection of the interior construction and assists materially in the radiation of the heat generated internally. Glasses are chosen for their high melting point, mechanical and thermal strength and insensitivity to rapid changes of temperature. A new design of valve of this kind for a main anode with grid is shown in Fig. 6.

The arrangement of a Brown Boveri single-anode mutator set with vacuum pump can be seen in Fig. 7. The set comprises six water-cooled tanks connected to the high-

[1] Brown Boveri Rev. 1944, Vol. 31, No. 9, p. 309–12.

vacuum pump by a common vacuum pipe. The cathodes, insulated from the tank, are each fastened by three feet to the underframe, which is itself insulated against earth; thus all cathodes are at the same potential. The outgoing bars leading to the cathode circuit-breaker are therefore connected to the underframe which also contains the various parts of the cooling system and the ignition device for each cathode or tank; this arrangement gives the set a neat and compact appearance and avoids specially insulating the cooling system. As the air pump set and the components of the cooling system are all at cathode potential, their motors, etc., are connected via a special isolating transformer to an earthed auxiliary supply. The anode terminals lie above the tanks and are joined by flexible connectors to the individual anodes. Supporting bearers between the vacuum tubing and the anode leads ensure that they remain in the correct position. The set, which with full phase control is rated 5000 A at 750 V, is assembled complete with accessories, so that on arrival at its destination only the electrical and cooling-water connections have to be made.

Pumped single-anode mutator sets can also be supplied with air cooling, as in many cases customers prefer this type to water-cooled mutators. An air-cooled mutator (Fig. 8) contains more or less the same main parts as the water-cooled model illustrated in Fig. 7. The tank, which is adapted to the new method of cooling, is generally provided with its own fan for cooling purposes. The latest Brown Boveri air-cooled single-anode mutators are rated at 3500 A, 750 V and are primarily intended for traction applications or systems with very changeable loading conditions. A set of this kind rated 1750 kW at 750 V is in service with an underground railway. As this set stands in a recess in the tunnel it had to be designed to fit in the available space. Due to the special running schedule of the railway, the set is designed for the loading diagram in Fig. 9. The overload periods, each lasting about an hour, recur four times in every twenty-four hours. During this hour thirty current peaks of 4800 A and fifteen of 7000 A each lasting 20 seconds, occur at 60-second intervals.

As a result of the splendid results obtained with the new design of valve construction in the single-anode mutators, particularly in respect of arc-extinction and regulation capacity, it was decided to completely redesign the air-cooled six-anode mutator. One of Brown Boveri's standard models, rated 2500 A at 750 V, is built to be suitable for the frequently recurring loading conditions of railway substations (Fig. 10). Due to the simple construction of the set these mutators lend themselves admirably to substations, which are usually arranged for automatic or remote control. A governing factor in the construction of the pumped air-cooled six-anode mutator is that in the event of a breakdown many customers, particularly in overseas territories, wish to be able to open the affected tank on the spot and repair it.

As mutator sets for main-line railways are housed in simply constructed substations at intervals of a few kilo-

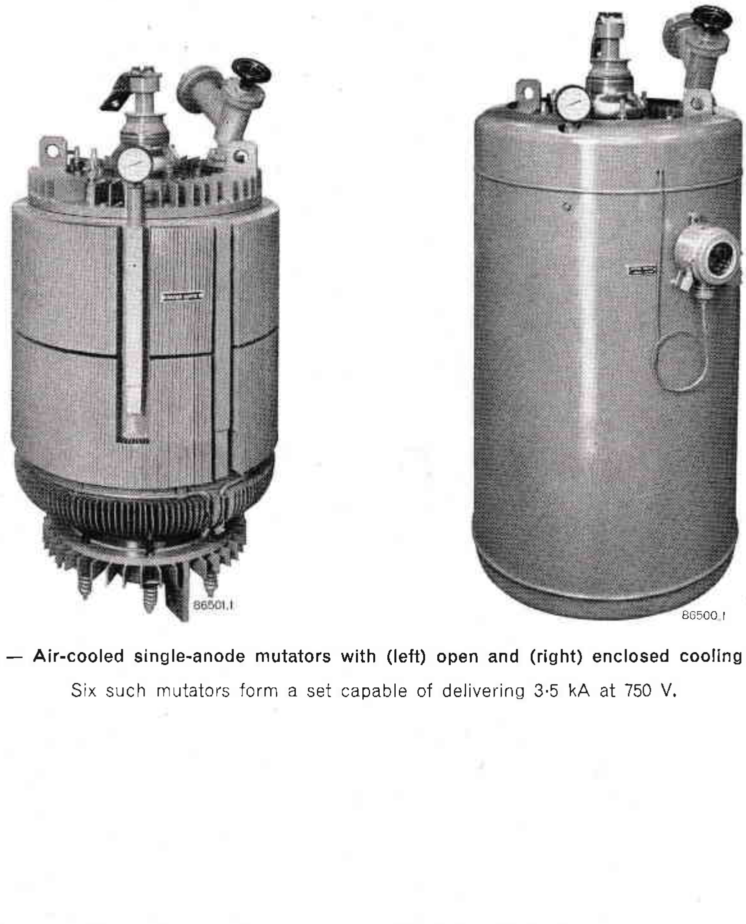


Fig. 8. — Air-cooled single-anode mutators with (left) open and (right) enclosed cooling system

Six such mutators form a set capable of delivering 3·5 kA at 750 V.

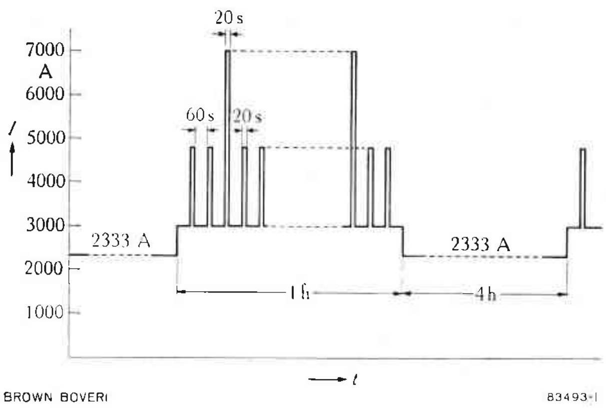


Fig. 9. — Loading diagram of an underground-railway substation

The set comprises six air-cooled single-anode mutators having a total output of 1750 kW at 750 V. The overload periods lasting one hour recur four times every twenty-four hours. During this hour thirty peaks of 4800 A and fifteen of 7000 A, each lasting 20 seconds, recur at 60-second intervals.

metres along the line, temperature variations must be taken into consideration, not only between summer and winter, but also between day and night. Sometimes such railways include mountainous routes with considerable differences in altitude, which make the mutator operating conditions very severe. Hence this type of mutator is fitted with special internal heating with appropriate temperature regulation. Under all operating conditions, regardless of ambient temperature, the mutator can always be maintained at a favourable working temperature.

Until quite recently almost all pumpless mutators with forced air cooling were supplied without grid control for the suppression of short circuits and back-fires. This simple model had fulfilled the requirements of the railways hitherto. Lately, however, the field of application of the pumpless six-anode mutator has rapidly expanded. Industry above all is showing considerable interest, as there is an increasing tendency towards individual feeding of motors, such as for driving rolling mills. Drives of this kind using variable-speed motors necessitate mutators with controlled grids for voltage regulation over a wide range. Under such conditions arc extinction and regulation of the mutator is no easy matter; from experience a pumpless six-anode tank is best in this respect. As a result of this fact Brown Boveri has developed an air-cooled pumpless mutator with controlled grids (Fig. 11); with full phase control its maximum rating is 1250 A at 750 V. Depending on the degree of phase control, it can be used for lower currents at correspondingly increased d.c. voltages, and also covers the voltage range for main-line traction where contact-wire voltages may reach 3600 V.

Finally, there is the interesting and important application of the pumpless single-anode mutator to locomotives. A number of railway authorities have initiated investigations into their possibilities. For one of these, commenced several years ago, Brown Boveri carried out the experimental installation of pumpless, air-cooled, single-anode tanks in locomotives, in order that their behaviour under such conditions might be observed. These tanks contain specially designed cathodes, the suitability of which was previously proved during trial runs. It stands to reason that mutator tanks for locomotives (Fig. 12) must be robust and unaffected by vibration, so that they will withstand the conditions characteristic of railway service.[1]

Prospects

From the present state of progress in mutator engineering it is more than likely that mutators with twelve

[1] See page 167.

Fig. 10. — Air-cooled mutator rated 1875 kW at 750 V or 4000 kW at 3600 V

This equipment is designed to meet the power requirements of a normal railway substation.

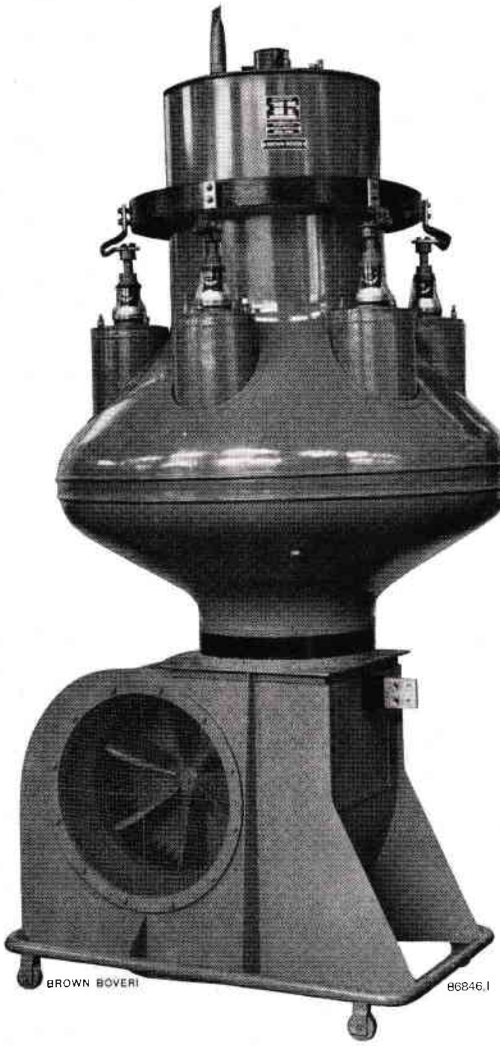


Fig. 11. — Pumpless, air-cooled mutator with controlled grids for voltage regulation and suppression of short-circuits and back-fires. Rating 930 kW at 750 V or 2000 kW at 3600 V

or more anodes will soon become obsolete. Admittedly their construction is simple and they do not need many accessories, which makes them quite easy to supervise and operate. But now that mutators are to be found working in almost every field of engineering involving a d.c. supply, the severity of the demands on reliability and regulation capacity has increased appreciably. On that account smaller units with one to six anodes prove more acceptable as regards weight, reliability and adaptability; thus recent years have seen the development of some significant new designs of this type. As the reliability of new types of mutator under all circumstances must first be corroborated by prolonged tests under every conceivable condition, it is a comparatively long time before such designs can be finalized and marketed. The new patterns, moreover, must be made to conform to certain principles so that the series will meet practical considerations from both the technical and the economic aspect.

When the new Brown Boveri mutators are used in heavy-current installations for continuous operation at their rated current, several units will be supplied from one high-power transformer. For this type of work water-cooled single-anode mutators are considered preferable, as they are capable of greater loading per anode or tank. The size of the transformer will be decided by the most economical unit rating, initial installation costs and efficiency. The total power output of such an installation usually necessitates banking of the mutator sets, subordinate groups being separately switched to avoid repercussions on the supply system. On the other hand, when a source of d.c. is required for traction or industrial purposes with low or moderate power and variable loading and

Fig. 12. — Pumpless, air-cooled, single-anode mutator with (left) open and (right) enclosed cooling system

This mutator, used in a mine locomotive, supplies a total of 1·6 kA at 960 V.

phase control, the six-anode air-cooled mutator, with or without vacuum pump, is likely to attract more frequent demand. It is anticipated that future developments will prove the correctness of the policy adopted by the Company. Whatever happens, scientific analysis and large-scale trials will be continued to provide still further information on the phenomena occurring inside mutators.

The experience gained in recent years has enabled Brown Boveri to bring out a complete new range of mutator types, permitting customers' requirements to be satisfied in respect of such factors as method of cooling and maintenance of vacuum, whilst keeping the number of types down to a minimum.

MS 821 (KME) *C. Brynhildsen*

MUTATOR LOAD CAPACITY

621.314.65.016.3

By way of introduction the author analyses the three functional operations which take place in a mutator—grid blocking, anode conduction (firing), anode blocking—and defines two terms essential to the treatment of the theme—Circuit Duty and Functional Capacity. He deals thoroughly with anode blocking, this being the first and most important part of the problem; in particular, anode blocking duty in controlled and uncontrolled mutators is calculated, followed by a description of the measurement of anode blocking capacity; finally load capacity curves are deduced.

Circuit Duty and Functional Capacity

A MUTATOR set is characterized by the number and type of gaseous discharge paths (i.e. anode, grid, cathode, subsequently referred to as valves) capable of current conversion, by the transformer connection, the load imposed and the operating duty. As all these characteristics are capable of manifold variation, a multiplicity of circuit arrangements and methods of operation can be devised, the exact mathematical analysis of which is complicated and tedious. For instructional purposes, therefore, the discharge paths are usually assumed to be replaced by ideal switches, and the d.c. circuit to include a very large choke. Then for both resistive and back-e.m.f. loading on the d.c. side the same conditions can be considered to obtain and only the effect of the various transformer connections requires investigation. This simplification to a single limiting case, which can be clearly illustrated theoretically in general terms, was first adopted in the pioneering treatise by W. Dällenbach and E. Gerecke [1][1] and since then has been employed almost exclusively in the study of mutators (conventional representation).

Using the above theory it is possible to calculate with ample accuracy the wave shape of all currents and voltages arising in any part of a mutator circuit. This still does not, however, give much help in deciding the correct design or mode of operation of a mutator: first one must know the laws by which, from electrical, thermal and mechanical considerations, the circuit duty of a mutator can be calculated from the current and voltage data. Under circuit duty can be included any influence, whether electrical, thermal or mechanical, whose increase leads to changes in, and finally destruction of, the object. Here, however, only the electrical duty of a mutator will be dealt with.

Determination of mutator duty is particularly difficult, as investigation of the physical properties of a gaseous discharge is usually carried out under laboratory conditions and not with the mutator in operation. Moreover, consideration of the discharge process or circuit problems alone will, of necessity, always remain inadequate. To solve the problem successfully it is essential to consider the overall picture of circuit and discharge. The question

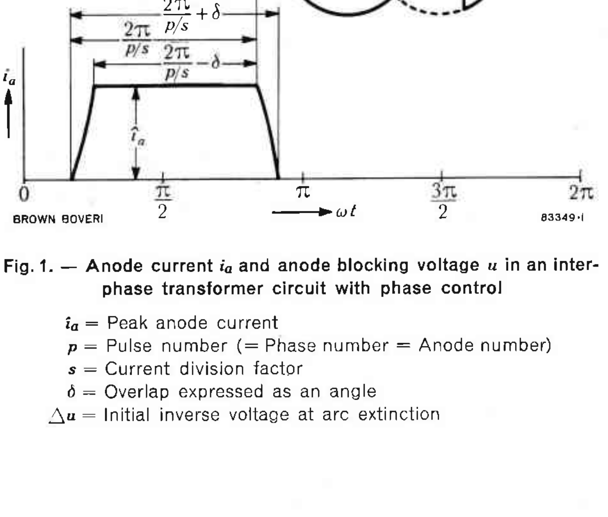


Fig. 1. — Anode current i_a and anode blocking voltage u in an interphase transformer circuit with phase control

$\hat{i}_a$ = Peak anode current
p = Pulse number (= Phase number = Anode number)
s = Current division factor
δ = Overlap expressed as an angle
Δu = Initial inverse voltage at arc extinction

[1] The figures in brackets refer to the bibliography at the end of the article.

of mutator duty will now be dealt with in the manner already indicated.

The voltage and current at the anode of a mutator are shown in Fig. 1. In this instance six-phase rectification with interphase transformer and phase control is being considered, where—according to the conventional representation—it is assumed that there is an infinitely large *cathode reactor and that operation is continuous.* To every cycle of the alternating current three quite separate intervals of time can be clearly recognized in respect of the rectifying elements:

(α) Grid blocking period (when the anode is positive with respect to the cathode but discharge is blocked by a negatively biased grid: function—grid blocking).

(β) Firing period (when the anode conducts the discharge current: function—firing).

(γ) Inverse or anode blocking period (when the anode is negative with respect to the cathode: function—anode blocking).

Table I lists the above functions, the quantities due to the external circuit and possible faults.

TABLE I

Period	Grid blocking period α	Firing period β	Anode blocking period γ
Regular mutator function	Grid blocking	Firing	Anode blocking
Circuit quantity	Anode blocking voltage	Anode current	Anode blocking voltage
Mutator quantity	Pre-discharge current	Arc voltage	After-current
Mutator duty	Grid blocking duty	Firing duty	Anode blocking duty
Mutator functional capacity	Grid blocking capacity	Firing capacity	Anode blocking capacity
Fault	Arc-through	Current interruption	Backfire

While the only distinction between the anode and grid blocking periods is in the polarity of the anode voltage with respect to the cathode, and the transition from period γ to α is not normally characterized by any particular events in the mutator, the periods α and β are separated by the ignition process, and β and γ by arc extinction.

For a given duty the operating condition envisaged is obviously that characterized by freedom from disturbances, the occurrence of faults defining the limit of the load capacity of a mutator. Having thus clearly established the difference between duty and load capacity, considerable progress has been made in the problem of designation. To make the above object clear, let us take as an example the nomenclature employed when considering the mechanical properties of materials, where a distinction is made between the extraneous forces exerted on a body and the resultant internal forces set up within that body, the force per unit area being known as stress. If the resultant stress in the body increases it finally attains a limit at which permanent mechanical changes take place; this is referred to as its strength. The relation of duty to load capacity (or stress to strength) is usually called the safety factor; it represents a measure of the reserve provided in a particular case. Mechanical stress is usually obtained as the result of a static or dynamic calculation, whereas strength is determined by technological tests.

To proceed analogously for mutators the electrical circuit duty is compared with the load capacity, which can also be denoted functional capacity. The duty should be calculated as a pure electrical quantity from the circuit and the nature of the load. On the other hand, the functional capacity, which depends on the design, properties of the materials and operating conditions (e.g. cooling), must be determined experimentally. From Table I a formula for the duty will now have to be found, as well as a measuring process to fix the loading limit of the mutator for each of the three operating functions.

So far only the conditions relating to continuous operation have been considered. From a practical point of view, however, it is most important to appreciate the behaviour of the mutator under transient conditions, i.e. at the instant of switching into circuit, on overload and when faced by a short circuit. This short enumeration alone shows how wide is the variety of functions and operating conditions and the number of investigations and measurements they involve. A description of the whole range of problems would require a correspondingly comprehensive treatment, for which, however, the available space would not suffice. Here, therefore, only a part of the problem, that of anode blocking during continuous operation, will be studied, investigations into the behaviour on overload and the remaining functions being reserved for a later article. As already mentioned, the definition of a particular mutator function comprises calculating the duty and measuring the functional capacity. Our study of anode blocking will therefore be commenced by computing the anode blocking duty.

Anode Blocking Duty under Steady-State Conditions

Definition of Anode Blocking Duty

In the early days of mutator engineering the blocking duty was usually characterized by the peak value of the inverse voltage, because it was at this value that the undesired glow discharge was able to develop most easily.

Later, when the occurrence of glow discharge during the inverse phase had largely been countered by the incorporation of deionizing and control grids, it was noticed that back-fires usually took place at the beginning of the blocking period, and they were logically considered to be connected with the process of commutation. A first attempt to characterize various circuits by means of quantities peculiar to the commutation process was made in 1935 by K. Müller-Lübeck [2] who proved that the product of the initial inverse voltage $\triangle u$ and the peak value of the anode current $\hat{\imath}_a$ divided by the overlap δ (see Fig. 2)

$$\frac{\triangle u\, \hat{\imath}_a}{\delta}$$

produced the same numerical result in all twelve-phase circuits ("Initial Inverse Voltage Law"). In 1939 K. H. Kingdon and E. J. Lawton [3], as the outcome of exhaustive experimental investigations, then discovered two governing factors: (a) for small anode-grid clearances, the product of initial inverse voltage $\triangle u$ and the commutation rate at the moment of arc extinction $(\mathrm{d}i_a/\mathrm{d}t)_\delta$

$$\triangle u \left(\frac{\mathrm{d}i_a}{\mathrm{d}t}\right)_\delta \tag{1}$$

and (b) for a gridless mutator

$$\hat{\imath}_a \triangle u^{1/4}$$

In 1940 W. Dällenbach and E. Gerecke [4] expressed duty by

$$\triangle u \left(\frac{\mathrm{d}i_a}{\mathrm{d}t}\right)_\delta \tau$$

where τ is a time governing the velocity of deionization; obviously there the intention was to give anode blocking duty the dimension of a power. Finally in 1953 W. Schmalenberg and O. Schiele [5] expressed the results of their observations as

$$\triangle u \left(\frac{\mathrm{d}i_a}{\mathrm{d}t}\right)_\delta \tau^2$$

which has the dimension of energy. In their publications, J. C. Read [6] and O. K. Marti [7] refer to the expression (1) as commutation or back-fire factor, though without furnishing any further experimental support. In view of this technically vague state of affairs exhaustive theoretical and experimental investigations have been in progress for some considerable time in the Brown Boveri mutator laboratory, which have proved conclusively that with the design of mutator usually adopted by the Company the anode blocking duty B is expressed by the term (1), i.e.

$$B = \triangle u \left(\frac{\mathrm{d}i_a}{\mathrm{d}t}\right)_\delta$$

This definition of anode blocking duty has the desired advantage that it allows mutator duty to be expressed solely in terms of the electrotechnical data of the circuit. As it is in no way dependent on the physical design, or technological or thermal conditions, it is understandable that it can provide no information regarding the physical causes of back-fires.

Physical Considerations

This definition of anode blocking duty is the outcome of measurements and experience, and may therefore be used as a reliable basis for subsequent investigations. But to be able to determine its range of validity, its physical implications will now be briefly outlined. During commutation the discharge current falls from its maximum value $\hat{\imath}_a$ (see Fig. 2) to zero. The positive and negative charge carriers (Hg-ions and electrons) which are present in almost equal numbers in the valve, are characterized in their behaviour by the so-called ion life τ [s] the duration of which depends on the physical dimensions of the valve and the density of the mercury vapour, as ions are continually being destroyed on contact with the walls and reproduced at the same rate in the valve. Thus ion concentration N [cm^{-3}] follows current variation but always with a slight delay, for which reason the discharge plasma has also been represented by a non-inductive resistance in series with an inductance [8]. When the arc is extinguished at the end of the firing period (when $i_a = 0$) a certain ion concentration N_δ still remains, causing a rapidly decaying stream of ions to flow to the negatively charged anode, which can be termed the "after-current". If the rate of change[1] of discharge current $(i = \hat{\imath} \cos [\pi t/(2 t_\delta)])$ at the end of the overlap period t_δ is expressed as

$$\left(\frac{\mathrm{d}i_a}{\mathrm{d}t}\right)_\delta = \frac{\pi}{2}\,\frac{\hat{\imath}_a}{t_\delta} \tag{2}$$

[1] A cosine wave-form is assumed for the current solely with a view to describing the physical events as simply as possible. The deduction of the exact formula for change of current appears under the next heading.

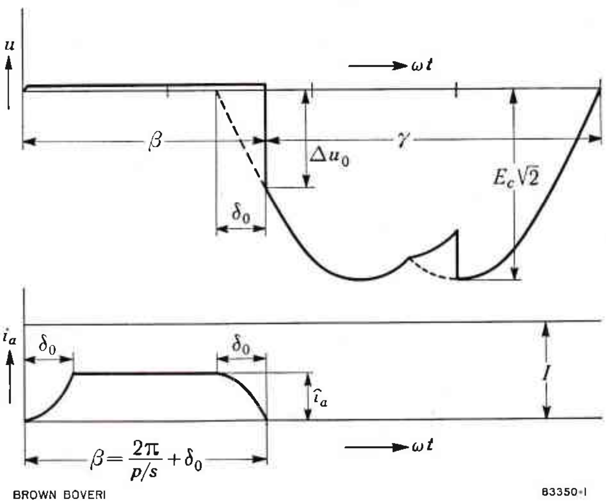


Fig. 2. — Anode current i_a and anode blocking voltage u in a two-phase uncontrolled (gridless) circuit with interphase transformer

E_c = Commutation voltage
s = Current division factor
I = Mutator current (d.c.)

The subscript $_0$ relates the associated quantity to uncontrolled operation.

calculation [9] will give the ratio, illustrated by Fig. 3, of the relative ion concentration at the end of overlap N_δ/N_0 (where N_0 is the concentration at the commencement of commutation, normally directly proportional to the discharge current $\hat{i}_a$), to the ratio of overlap to ion life t_δ/τ. When the rate of change of the current is small (i.e. $t_\delta/\tau \gg 1$), the relative ion concentration is given by

$$\frac{N_\delta}{N_0} = \frac{\pi}{2}\,\frac{\tau}{t_\delta} \tag{3}$$

As, for constant vapour density, τ is solely dependent on the physical dimensions, and thereby becomes a constant for the vessel, the ion concentration N_δ is only dependent on the overlap δ or, taking into consideration equation (2), on the current gradient di_a/dt:

$$N_\delta = \frac{N_0}{\hat{i}_a}\,\tau\left(\frac{d i_a}{d t}\right)_\delta \sim \left(\frac{d i_a}{d t}\right)_\delta \tag{4}$$

as observations prove. If, on the other hand, the current varies rapidly (so that $t_\delta \ll \tau$), there is no appreciable variation in ion concentration and

$$N_\delta \approx N_0 \tag{5}$$

The physical background to the formula for circuit duty has thus been indicated and its range of validity outlined. Obviously formula (1) will only apply when overlap is much greater than ion life τ. When the overlap is extremely short, as when τ is large (due to high vapour pressure or a wide discharge vessel), the previously assumed relation ($t_\delta/\tau \gg 1$) is no longer fulfilled and the duty formula cannot be used. This situation must be borne in mind in choosing a suitable method of testing.

Anode Blocking Duty in Uncontrolled Mutators

To be able to obtain a clear picture of the various relationships, let us first study the conditions of uncontrolled operation (Fig. 2). (When referring to delay angle $\alpha = 0$, the suffix 0 will be added). The expression for anode blocking duty corresponding to (1) becomes

$$B_0 = \Delta u_0 \left(\frac{d i_a}{d t}\right)_{\delta_0} \tag{1a}$$

To simplify the practical application of this quantity let us now write it in more tangible form using certain known relations. Initial inverse voltage is given by

$$\Delta u_0 = E_c\sqrt{2}\sin\delta_0 = U_{00}\,s\,\frac{2\pi}{p}\sin\delta_0 \tag{6}$$

where $s = I_0/\hat{i}_a$, the current division factor (for midpoint connection $s = 1$; with interphase transformer $s = 2$ or 3), p = pulse number and E_c the commutation voltage, which has a r.m.s. value of $E_c = 2\,E\,\sin s\pi/p$ (E = transformer phase voltage), and is related to the no-load voltage

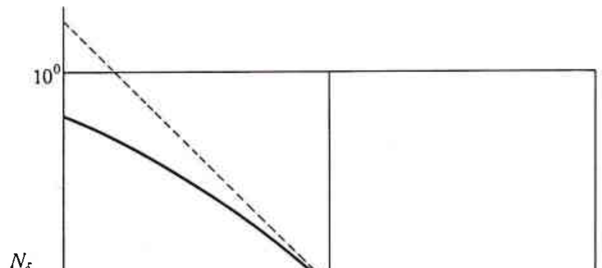


Fig. 3. — Relative ion concentration after firing (the ratio of N_δ to the concentration before overlap N_0) as a function of the relative overlap (the ratio of t_δ to ion life τ)

$$U_{00} = E\sqrt{2}\,\frac{p}{s\pi}\,\sin\frac{s\pi}{p}$$

by

$$E_c = U_{00}\sqrt{2}\,\frac{s\pi}{p}$$

The gradient of the anode current at the moment of extinction

$$\left(\frac{\mathrm{d}i_a}{\mathrm{d}t}\right)_{\delta_0} = I_c\sqrt{2}\,\omega\,\sin\delta_0$$

(I_c = r.m.s. value of the short-circuit current during commutation; $\omega = 2\pi f$ = angular frequency) can be expressed as follows using $\hat{\imath}_a = I_c\sqrt{2}(1-\cos\delta_0)$:

$$\left(\frac{\mathrm{d}i_a}{\mathrm{d}t}\right)_{\delta_0} = \hat{\imath}_a\,\omega\,\frac{\sin\delta_0}{1-\cos\delta_0} = I_0\,\frac{\omega}{s}\,\frac{\sin\delta_0}{1-\cos\delta_0} \tag{7}$$

By multiplying the two factors expressed in (6) and (7), we obtain for the anode blocking duty of an uncontrolled mutator the following expression:

$$B_0 = U_{00}\,I_0\,\frac{2\pi}{p}\,\omega\,\frac{\sin^2\delta_0}{1-\cos\delta_0} \tag{8}$$

For the specific potential drop

$$\varepsilon_0 = \frac{\Delta U_0}{U_{00}} = 1 - \frac{U_0}{U_{00}}$$

the following relation holds good:

$$\varepsilon_0 = \frac{1}{2}(1-\cos\delta_0)$$

from which

$$\frac{\sin^2\delta_0}{1-\cos\delta_0} = 1+\cos\delta_0 = 2(1-\varepsilon_0) = 2\,\frac{U_0}{U_{00}}$$

thus allowing equation (8) to be written in even simpler form:

$$B_0 = U_{00}\,I_0\,\frac{\pi}{p}\,\omega\,4(1-\varepsilon_0) = U_0 I_0\,\frac{\pi}{p}\,8\pi f \approx P_0\,\frac{f}{p}\cdot 80 \tag{9}$$

This expression shows that the anode blocking duty is only dependent on the d.c. power ($P_0 = U_0 I_0$), the supply frequency f and the pulse number p. For normal systems, where $f = 50$ c/s, and a six-phase circuit

$$B_0 = 666\,P_0 \tag{10}$$

Consequently, if a particular pulse number p is stipulated, the *transformer connection*, and also the impedance voltage, will have *no effect on the anode blocking duty* B_0. The reason for this important rule can be found in the fact that when the overlap δ is prolonged the increase in the initial inverse voltage Δu is balanced by a corresponding reduction in ion concentration N_δ or the after-current (Fig. 3).

Anode Blocking Duty in a Phase-Controlled Mutator

With *phase control* (Fig. 1) the expressions given in the previous section are changed with respect to the delay angle as follows:

$$\Delta u = E_c\sqrt{2}\sin(\alpha+\delta) = U_{00}\,s\,\frac{2\pi}{p}\,\sin(\alpha+\delta)$$

$$\left(\frac{\mathrm{d}i_a}{\mathrm{d}t}\right)_{\delta} = \frac{I}{s}\,\frac{\omega\,\sin^2(\alpha+\delta)}{\cos\alpha-\cos(\alpha+\delta)}$$

Whence the anode blocking duty is given by

$$B = U_{00}\,I\,\omega\,\frac{2\pi}{p}\,\frac{\sin^2(\alpha+\delta)}{\cos\alpha-\cos(\alpha+\delta)} \tag{11}$$

or as a function of the duty in uncontrolled operation

$$\frac{B}{B_0} = \frac{\sin^2(\alpha+\delta)(1-\cos\delta_0)}{[\cos\alpha-\cos(\alpha+\delta)]\sin^2\delta_0}$$

When I is constant, $\cos(\alpha+\delta) = \cos\alpha + \cos\delta_0 - 1$ which finally gives the relation of anode blocking duty to delay angle:

$$\frac{B}{B_0} = \frac{\sin^2(\alpha+\delta)}{\sin^2\delta_0} \tag{12}$$

Here the powerful influence of transformer impedance on anode blocking with phase control can be observed, which is exactly contrary to uncontrolled operation. If with phase control the anode blocking duty B is intended to be kept constant, this can be achieved by correspondingly reducing B_0, and increasing the anode impedance or angle of overlap δ_0. In relation to the constant value of B we immediately obtain the following from eq. (12)

$$\frac{B_0}{B} = \frac{\sin^2\delta_0}{\sin^2(\alpha+\delta)} = \frac{\sin^2\delta_0}{\sin^2[\arccos(\cos\alpha+\cos\delta_0-1)]} =$$

$$= \frac{4\,\varepsilon_0(1-\varepsilon_0)}{\sin^2\alpha + 4\,\varepsilon_0(\cos\alpha-\varepsilon_0)} \tag{13}$$

This relation, a fundamental equation in planning mutator installations, is illustrated graphically in Fig. 4 as a function of the degree of control a obtained with various overlaps δ_0, where degree of control is defined by

$$a = \frac{U_{a0}}{U_{00}} = \cos\alpha$$

($U_{\alpha 0}$ being the no-load d.c. voltage when the delay angle is α). For "no-volt" operation ($\alpha = 90°$) equation (13) can be simplified as follows:

$$\frac{B_0}{B_{90°}} \approx \frac{4\,\varepsilon_0(1-\varepsilon_0)}{1-4\,\varepsilon_0^2} \tag{14}$$

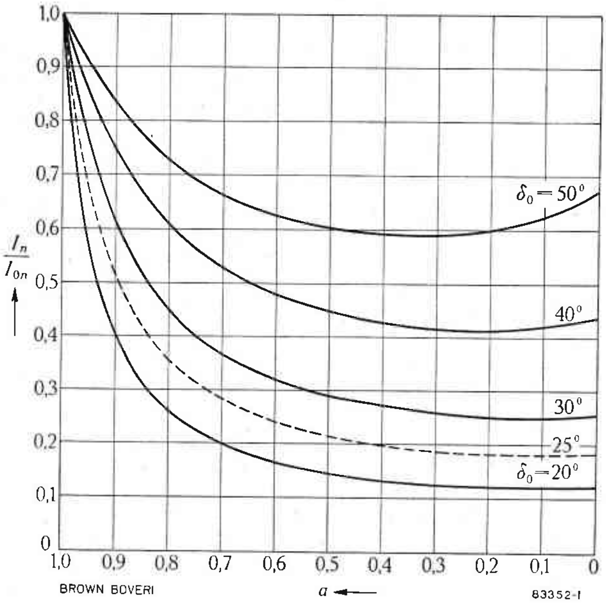


Fig. 4. — Current rating reduction with phase control to give constant anode blocking duty in the region of power limitation

a = Degree of control
I_n = Current rating
I_{on} = Current rating for uncontrolled operation

As the transformer impedance voltage u_K is frequently used to denote commutation impedance or angle of overlap δ_0, Table II below gives numerical values for some of the most frequently used connections.

TABLE II

	Mid-point connections					Bridge connections	
Connection							
$\frac{\varepsilon_0}{u_K}$	0·707	0·866	1·500	0·500	0·707	0·707	0·500

Anode Blocking Capacity

Definition

As the anode blocking duty of a mutator is increased a limit is eventually reached, defined as the anode blocking capacity A, above which the number of blocking failures and back-fires increases to intolerable proportions. Of the mutator functions mentioned in the introduction, anode blocking assumes by far the greatest importance, which explains the common practice of referring simply to "load capacity" instead of the more accurate term suggested (anode blocking capacity). The subject under discussion having so far been kept within definite limits the shorter term can be used from now on without risk of misunderstanding.

Various theories concerning the causes of back-fires are based on classical laws, whereas J. Slepian and L.R. Ludwig [10] were able to show that back-fires obey statistical laws. Previous attempts to bring the classical theories and statistical facts into line had, up to a point, always met with considerable difficulties, but in the meantime an explanation was discovered [11].

From back-fire statistics it is evident that there is no clear line of demarcation, on one side of which back-fires will occur and on the other will not. Moreover, the reliability of the mutator is only a function of the probability of back-fire W, and after all the limit of load capacity can only be defined by agreement (by stipulating a certain probability of back-fire).

The permissible probability can be studied from different angles. A customer will generally only be interested in the total number of back-fires occurring in his mutator plant (W_{plant}). It is quite unimportant to him how many anodes there are and how high their specific load may be. The designer on the other hand prefers to judge the average number of back-fires of one particular anode (W_1). This outlook is the natural outcome of dealing with the constructional and technological characteristics and peculiarities of individual anodes.

To reconcile these two conflicting aspects a compromise must be reached and it is therefore proposed to study the probability of back-fire of six anodes (W_6), the number usually grouped together to form an independent unit.

Regarding the permissible magnitude of back-fire probability there are likewise a variety of opinions. In the USA, for instance, it is stipulated that no more than one back-fire should occur per anode per year [12] ($W_1 \leqq 5 \times 10^{-10}$). The probability of back-fire of one anode (W_1) is defined as the ratio of the number of back-fires to the total number of cycles in the observation period. For example, one year's continuous operation (8760 h) at 60 c/s amounts to roughly 2×10^9 cycles. One back-fire in this period represents therefore a probability of $W_1 = \frac{1}{2} \times 10^{-9} = 5 \times 10^{-10}$. For some time now considerably better results have been obtained in practice in Europe and in some cases, after continuous operation in electrolysis installations for a number of years, probabilities of one back-fire per eighteen anodes per year have been achieved, which means

$$W_1 \approx 5{\cdot}6 \times 10^{-12}$$

Although any such definition will always, to a certain extent, be laid down arbitrarily, the value of

$$W_6 \lessapprox 10^{-10} \text{ or } W_1 \lessapprox 1{\cdot}67 \times 10^{-11}$$

is suggested as a conservative estimate; this works out to an average of one back-fire to six anodes in one year's continuous operation at 50 c/s. Mutators with an average back-fire rate of this order can well be designated "good"; which also paves the way for a degree of grading according to quality. The tolerable number of back-fires will always be governed by the nature of the operation; for instance applications such as low-voltage traction are considerably less exacting than say a rolling mill.

From the foregoing, the anode blocking capacity A (or load capacity) of an anode can be so defined that A is numerically equal to that anode blocking duty B with which the probability of back-fire W_6 has the value 10^{-10} or $W_1 = 1{\cdot}67 \times 10^{-11}$.

Measurement of Anode Blocking Capacity

The definition of load capacity by means of the probability of back-fire is of theoretical value only as long as there is no process of testing and measurement by which load capacity, i.e. the average number of back-fires in relation to the duty, can be determined. Various investigations were carried out with this in mind (e.g. the so-called accelerated tests [13, 14]); their results, however, cannot yet be considered satisfactory. Fundamentally, only those methods of testing giving full consideration to the statistical character of back-fires can be expected to achieve success. Such a method is the circuit used by K. H. Kingdon and E. J. Lawton [3] in which the electrical blocking duty can be increased to such a degree that sufficient back-fires occur in a short time to make definite evaluation possible. The application of such an accelerated process is of course bound by the condition that the results should also be applicable satisfactorily to the practical case in point.

As, to the author's knowledge, no attempt had ever been made to determine the extent to which the results obtained from the above test circuits agree with the behaviour of a mutator in practice, exhaustive tests were carried out over a long period in the Company's mutator laboratory to study this aspect of the problem. These showed that such circuits do in fact determine the anode blocking capacity correctly and by using Poisson's formula it is possible to extrapolate for the remainder of the normal range of mutator duty. The validity of Poisson's equation was verified for a probability range of roughly 10^8, thus corroborating the reliability of the method employed. The use of Poisson's Law necessitates, of course, a certain amount of circumspection and experimental care, if reproducible results are to be obtained.

The Poisson formula used for this extrapolation

$$W = \frac{\mu^n}{n!} e^{-\mu} \tag{15}$$

is a well-known statistical formula, indicating the probability W of a quantity attaining the value n, when its average is only μ. The numerical evaluation of this equation is illustrated graphically in Fig. 5. For the occurrence of back-fires, the equation can, for instance, be so interpreted, that, with the probability obtained from the formula, n electrons will be liberated in a process of

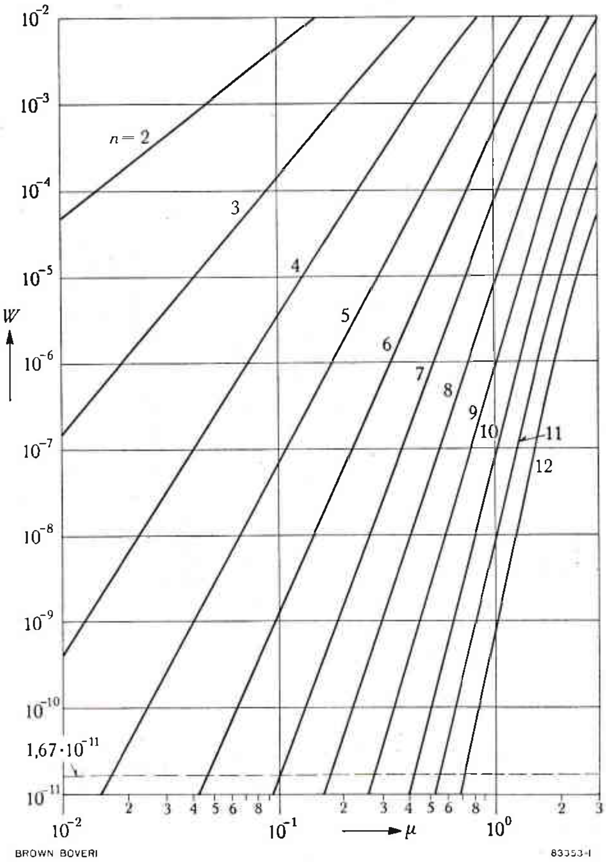


Fig. 5. — Poisson's equation expressed graphically

Probability W of a quantity attaining the value n when its mean value is only μ

2–12 = Valve quality n

ionization or emission where on an average only μ are liberated. Consequently, Poisson's formula can be successfully applied direct to the problems posed by the anode blocking process in mutators. Although this formula has frequently been employed [3, 10, 15] to interpret the physical aspect of investigations into back-fires, its fundamental significance in mutator engineering has obviously not been recognized so far. Using the Poisson distribution it is possible for instance to calculate the probability of back-fire in relation to the blocking duty, the operating conditions (temperature of the cooling agent, etc.) entering as parameters.

The investigations into the applicability of Poisson's equation to the definition of mutator load capacity produced the following results: The mean value μ of the quantity in equation (15) liable to variation can be expressed as a straightforward function of anode blocking duty B by means of the empirical equation

$$\mu = 3{\cdot}9 \times 10^{-11}\, B \tag{16}$$

The investigations also established the value of n as a measure of the quality of the valve and it will therefore be referred to as "valve quality". This depends both on constant factors such as design, properties and treatment of materials, and on the variable factor, the temperature of the cooling agent. In Fig. 6 the valve quality n is expressed, from equation (15), as a function of the mean value μ of the probability of back-fire $W_1 = 1{\cdot}67 \times 10^{-11}$ which was suggested as a standard. In line with the definition, the duty B which produces this probability is numerically equal to the anode blocking capacity A. In order that the graphical representation in Fig. 6 may be understood more easily, equation (16) and the definition $A = B$ (when $W_1 = 1{\cdot}67 \times 10^{-11}$) are used to provide the abscissa with a second scale for anode blocking duty A. As, however, from eq. (10) the d.c. power of an *uncontrolled* six-anode mutator is in a fixed ratio to the resultant anode blocking duty, this also gives (for $W_1 = 1{\cdot}67 \times 10^{-11}$) the permissible d.c. power rating P_{0n}.

$$P_{0n} = \frac{A}{666} \tag{17}$$

which can likewise be read direct from a third abscissa scale in Fig. 6. A graph such as Fig. 6 thus permits determination of the minimum valve quality necessary to obtain a given d.c. power rating or alternatively the maximum permissible d.c. power for a given valve quality.

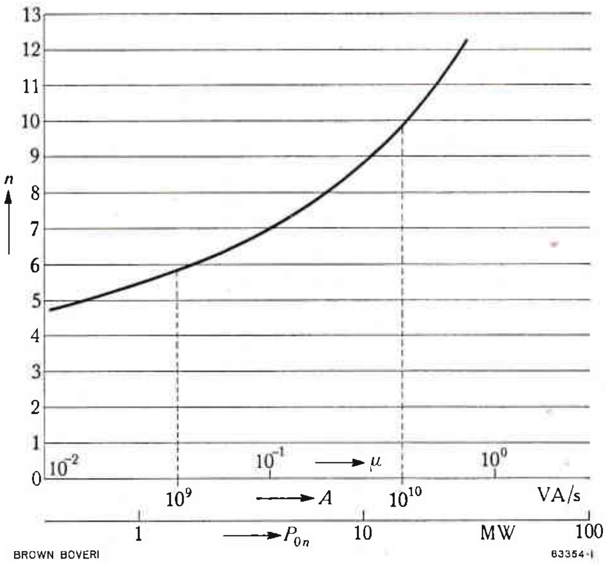


Fig. 6. — The relation, given by Poisson's equation, for a probability $W = 1{\cdot}67 \times 10^{-11}$, between valve quality n and the quantity μ, or anode blocking capacity A, or the d.c. power rating P_{0n} of a gridless six-phase mutator

In the practical application of Poisson's formula it is usual to determine the valve quality n of the design in question using a suitable test circuit. For this the average back-fire probability W_1 must be measured as accurately as possible taking several values of B, the anode blocking duty, at a constant cooling temperature. The readings are plotted to form a curve, which is then interpolated in the family of curves in Fig. 5, whence the value of n can be determined. Extrapolating this empirical curve until it intersects the straight line $W_1 =$ constant (e.g. $1{\cdot}67 \times 10^{-11}$) the numerical value of μ can be obtained and from eq. (16) the appropriate blocking capacity A for the cooling-medium temperature at which the measurements were taken. If further observations are made at other temperatures, correspondingly different values of n and A are obtained. The relationship between the two, which has been known for a long time, is illustrated in Fig. 7; this curve indicates that as the cooling-medium temperature is reduced the anode blocking capacity A rises, and vice versa.

Load Capacity Curves

For practical purposes it must be possible to state, for a given mutator, the main electrical quantities (current I and voltage U) as a direct function of the cooling-medium temperature t. Therefore a series of straight lines (dotted) has been drawn in a loglog system of coordinates in Fig. 8, which (in line with Fig. 7) represents

the anode blocking capacity at various cooling-medium temperatures. As was established by eq. (17), the d.c. power rating of an uncontrolled mutator is directly proportional to its blocking capacity A, which explains why this series of straight lines portrays constant-power characteristics. These curves are only valid in a definite region determined by the design of the mutator. The constant-power curves terminate at certain currents and voltages and are continued by curves following other laws. Thus anode blocking capacity is given by a composite curve having three sections:

I. Current limitation
II. Power limitation
III. Voltage limitation

With a view to generalization the axes of the coordinates are provided with relative scales. The voltages are related to a standard d.c. voltage U_{01} (e.g. 750 V corresponding to IEC standards). The standard power P_{01} is defined for a stipulated mean cooling-water temperature and the currents are referred to a standard current I_{01}. Current and voltage limits are to a large extent fixed by the design.

If the curve in the area of voltage limitation were to adhere strictly to physical laws, reduction in voltage would

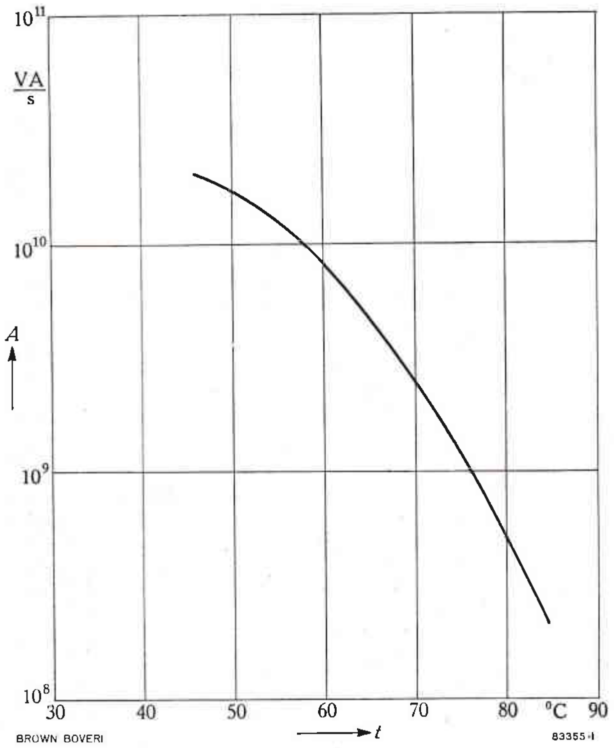


Fig. 7. — The relation between anode blocking capacity A and saturated Hg-vapour temperature t to give a back-fire probability of $W_6 = 10^{-10}$

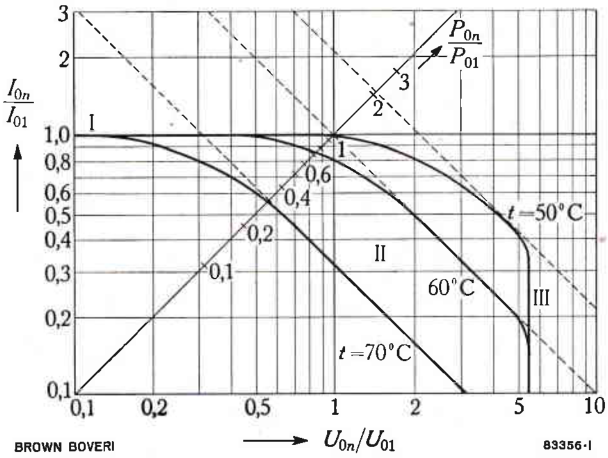


Fig. 8. — Load capacity curves of an uncontrolled mutator for various temperatures t of the cooling medium

I = Current limitation II = Power limitation III = Voltage limitation

I_{0n}, U_{0n}, P_{0n} = Current, voltage and power ratings of an uncontrolled mutator

I_{01}, U_{01}, P_{01} = Standardized values of current, voltage and power in an uncontrolled mutator

always imply a rise in current. The steepness of the curve would, it is true, decrease gradually, but it would not finally become horizontal, as in Fig. 8. In practice, however, this refinement has been somewhat ignored and in the case in point the simpler representation is accepted on account of the constancy of the current at low voltages. When the current limitation is fixed by a variable (a mutator component) which does not help to define A, other conditions will obtain.

In any attempt to deduce the load capacity of a phase-controlled gridless mutator from its power curve, it must be borne in mind that the anode blocking duty increases with phase control, but that the anode blocking capacity has a constant value irrespective of the delay angle. In conjunction with eq. (12) and (17) this means that within the area of power limitation of a mutator

$$\frac{P_n}{P_{0n}} = \frac{B_0}{B} = \frac{\sin^2\delta_0}{\sin^2(\alpha+\delta)} \tag{18}$$

where P_n is the d.c. power rating with phase control and P_{0n} the d.c. power rating without grid control. This gives the d.c. power rating for a certain delay angle. At a given d.c. voltage U the power rating reduction factor P_n/P_{0n} will agree with that of the current rating I_n/I_{0n} (where I_n = current rating with phase control and I_{0n} = current rating without control). The current reduction curves in Fig. 4 are valid for the region of power limitation.

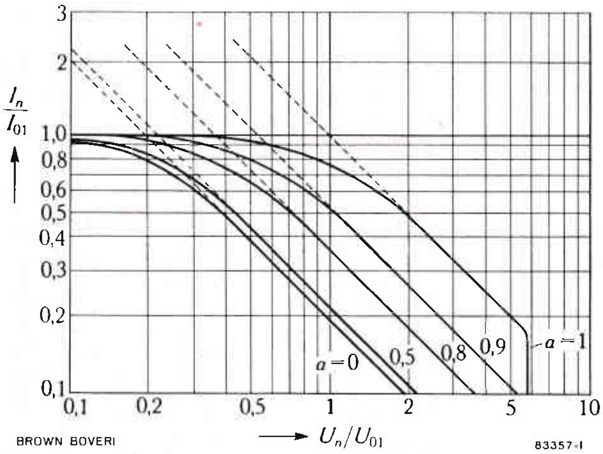


Fig. 9. — Reduction in mutator rating figures with respect to the degree of phase control a for cooling-medium temperature $t = 60°C$ (with interphase transformer; impedance voltage $u_K = 10\%$)

In the region of current limitation the blocking capacity A steadily decreases with rising current rating. The rate of change of this function can be obtained from the load capacity curve of the uncontrolled mutator, as, according to eq. (17), the sole difference between P_{0n} and A is a numerical factor. Thus the formula for power rating reduction with phase control (18) may only be used on condition that P_n and P_{0n} are related to the same rated current, as only then is the ratio of the two quantities to the current equal and omissible from the relationship. A power reduction at constant current implies a reduction in rated voltage, or in Fig. 9 a parallel realignment of the P_{0n} curve in the ratio $U_n / U_{0n} = B_0 / B$ to obtain the P_n curve. As the curvature of the P_{0n} curve depends on the design of the tank, in the region of current limitation no attempt will be made to find a generally valid analytical explanation and the load capacity with phase control will be determined by graphical means. Fig. 9 shows a family of curves for various degrees of phase control, from which a law can be recognized, well known to the specialist, that with diminishing rated voltage for a given degree of phase control a the necessary reduction in current rating $\triangle I_n = I_{0n} - I_n$ is likewise decreased.

If, on the other hand, the duty of a mutator coupled to a given transformer is required to be maintained at the same level B_0 with and without phase control, this can be achieved—as in such a case the transformer impedance is invariable—but only for relatively small delay angles (i.e. $\alpha \leq \delta_0$) and by drastically reducing the current in the proportion given by the following relation simply deduced from the equation $\alpha + \delta = \delta_0$:

$$\frac{I}{I_0} = \frac{\cos\alpha - \cos\delta_0}{1 - \cos\delta_0}$$

Examining (17) and (18) more closely, we discover that with phase control the duty is reduced most effectively by increasing the impedance on the anode side, to which end the power rating of the transformer at a given impedance voltage is measured in the manner described above (corresponding to P_n / P_{0n}).

Safety Factor

Calculations and experimental investigations are always based on definite (ideal) operating conditions. Frequently when considering a practical case one proceeds in accordance with this ideal situation without first posing the very important question of how far the actual operating conditions agree with the assumed (ideal) specification. Consideration of this difference between the ideal and the actual state is consequently of fundamental importance and will now be briefly described. Thereby, in the main, there are two distinct groups of factors, the one referring to circuit quantities, the other to mutator characteristics.

The true state of the quantities arising from the circuit arrangement is characterized by definite deviations from the ideal values on which the calculation was based. Whereas, for example, the calculation always assumes a symmetrical a.c. supply, there are nearly always slight asymmetries in the supply system and the transformer. The calculation also always assumes the secondary voltage of the transformer to have a pure sine-wave form, whereas in actual fact there are small distortions caused by the fifth and seventh harmonics.[1] In addition there are influences of a transient nature, as the characteristic impedances may be subject to temporary variation.

Whereas the fluctuations of the circuit quantities usually remain within narrow limits, the variations in mutator properties which will now be studied have considerably higher numerical values. These variations, due to deviations from the specified figures of geometry and technology, that is to say manufacturing and operating tolerances (e.g. temperature variations of the cooling medium) are much more difficult to keep within narrow limits; frequently not even the amount of variation is known.

To be able to predict the behaviour of a mutator, certain conditions regarding the fluctuation of the mutator properties must be assumed. For example, tolerances are set up

[1] See p. 144 of this issue.

for certain dimensions in manufacture and these define the permissible degree of variation. Moreover, the quality of the materials employed is checked by exhaustive technological tests before use. Finally, care must be taken to ensure that formation is carried out in the correct manner and that when the mutator is in service the cooling medium maintains the prescribed temperature. Much will depend, for instance, on the thermostat elements employed or the method chosen to regulate cooling, when determining between what limits the temperature of the cooling medium can vary. In this connection, temperature regulation under very changeable loading conditions warrants particular attention.

MS 778 (KME) *T. Wasserrab*

Bibliography

[1] W. Dällenbach and E. Gerecke: Die Strom- und Spannungsverhältnisse der Grossgleichrichter. Arch. Elektrotech. 1924, Vol. 14, p. 171–248.

[2] A. Glaser and K. Müller-Lübeck: Theorie der Stromrichter. Vol. I. Springer Verlag, Berlin 1935.

[3] K. H. Kingdon and E. J. Lawton: The Relation of Residual Ionization to Arc-Back in Thyratrons. Gen. elect. Rev. 1939, Vol. 42, p. 474–8.

[4] W. Dällenbach and E. Gerecke: Entwicklungen und Fortschritte im Bau von Eisengleichrichtern. Elektrotech. Z. 1940, Vol. 61, p. 705–9 and 734–8.

[5] W. Schmalenberg and O. Schiele: Anodenrückstrom-Kennlinie und Stromkreisdaten als Mass für die Beurteilung von Quecksilberdampf-Stromrichtergefässen. Phys. Verhandl. 1953, Vol. 4, p. 184.

[6] J.C. Read: High-Voltage Steel-Tank Mercury-Arc Rectifier Equipments for Radio Transmitters. J. Instn elect. Engrs 1945, Vol. 92/II, p. 453–68.

[7] O.K. Marti: Status of Mercury-Arc Power Rectifiers. CIGRE 1946, Report No. 114.

[8] W.O. Schumann: Ueber die Beeinflussung von Entladungsplasmen durch elektrisch gesteuerte Gitter Arch. Electrotech. 1941, Vol. 35, p. 437–44.

[9] T. Wasserrab: Die positive Säule bei veränderlichem Entladungsstrom. Z. angew. Phys. 1955, Vol. 7, No. 4, p. 176—9.

[10] J. Slepian and L. R. Ludwig: Backfires in Mercury-Arc Rectifiers. Trans. Amer. Inst. elect. Engrs 1932, Vol. 51, p. 92–104.

[11] T. Wasserrab: Die statistischen Gesetzmässigkeiten der Mutator-Rückzündungen. Sci. Elect. 1954, Vol. 1, No. 3, p. 112–26.

[12] Mercury-Arc Power Converters in North America (an AIEE Committee Report). Trans. Amer. Inst. elect. Engrs 1948, Vol. 67, p. 1031–60.

[13] H.L. Kellogg: The Testing of Mercury-Arc Rectifiers. Trans. Amer. Inst. elect. Engrs 1943, Vol. 62, p. 765–73.

[14] C.C. Herskind: Rectifier Capacity. Trans. Amer. Inst. elect. Engrs 1946, Vol. 65, p. 667–70.

[15] H.C. Steiner, J.L. Zehner, and H.E. Zuvers: Pentode Ignitrons for Electronic Power Converters. Trans. Amer. Inst. elect. Engrs 1944, Vol. 63, p. 693–7.

THE CHOICE OF TOTAL PHASE NUMBER FOR HIGH-POWER MUTATOR AND CONTACT-CONVERTER INSTALLATIONS

621.314.626
621.314.65

The present article examines the nature and significance of the repercussions on the remainder of the supply system of the primary current harmonics produced in mutator and contact converter installations. The author then describes methods of alleviating these effects and outlines the factors governing the choice of the total number of phases.

THE wave-form and harmonic content of the supply current of contact converters are almost identical with those of mutators having the same number of phases. The following arguments can therefore be applied with equal validity to either type of converter which, for the sake of brevity, will henceforth be referred to as mutators.

The presence of harmonics in the primary current of mutators already gave rise to serious doubts in the minds of electricity supply authorities when the first rectifier stations were erected some forty years ago. With the construction of large conversion plants having outputs of 50 MW and above, the significance of harmonics becomes more and more pronounced and justifies the study of these problems. These questions will now be examined—without any claim to completeness—particularly in respect of the choice of the total number of phases or, to keep to the new terminology, the pulse number of large mutator and contact-converter installations. It is assumed that the reader is already familiar with the relative values of the harmonics of mutators [1, 2, 3].[1]

The Requirements of the Mutator

For present unit ratings it is quite clear that, from the aspect of the material required in the construction of a mutator and its immediate accessories for cooling, excitation and vacuum maintenance, the adoption of six, or in exceptional cases twelve, as the pulse number results in the most economical design, since a set with six or twelve anodes (or contacts) can nowadays convert power of the order of 4 to 8 MW continuously. From the standpoint of the mutator itself, there is no apparent reason for the pulse number of a set being more than six. Consideration of the grid control gear for voltage regulation alone will demonstrate the wisdom of keeping to the number six. From the point of view of design, too, it is clear that the six-phase transformer is not only the cheapest, but also the most reliable. Apart from interposing special phase-shift transformers between the main transformer and the mutator, a larger phase number can only be attained—with a primary winding common to each leg of the transformer—by winding several dephased secondaries over each primary. This means that there would be several secondaries at different potentials on each leg which would render the transformer more expensive and decrease its short-circuit strength. From the aspect of transformer construction, the six-phase type is therefore also the best solution. If, for cogent reasons, it is decided to use a twelve-phase set, it is advisable—to obtain equal reliability and approximately the same space requirements—to provide the transformer with an intermediate yoke and to arrange the primary winding of one half of the transformer in star and the other half in delta. The intermediate yoke then enables the sections of each leg connected to it to be fed quite simply with mutually dephased voltages. Though more extravagant, the same result can be obtained with the zig-zag arrangement, the primary winding of each half being dephased $\pm$ 15° in opposite senses. Thus all important factors, both in respect of the mutator itself and of the associated transformer, point conclusively to the adoption of six, in special cases twelve, as the pulse number for a single set.

So far only the design of a single set has been mentioned, but now the installation as a whole must be considered. In cases where, for reasons still to be stated, the choice of a pulse number p greater than six for the installation is unavoidable, phase-shift transformers are available in addition to the means already described for a twelve-phase set. These are connected as auto-transformers in series with the mutator transformers and maintain a constant phase angle between the vector triangles of the incoming and outgoing voltages. For this purpose one phase-shift transformer can be allotted to each set or be made to serve several in-phase or out-of-phase sets. This displacement of one group with respect to another has the effect that, under certain circumstances resulting from the phase difference between the various harmonics of the same supply phase, a definite group of harmonics disappears

[1] The figures in brackets refer to the bibliography at the end of the article.

from the totalized primary current of several mutator sets forming a polyphase system. This is only true on condition that the anode voltages of the same system together form a symmetrical polyphase system and that the loading, overlap and regulation of the grid voltage are equal in all sets. For example, when four six-phase sets, each mutually dephased by 15°, are banked to obtain a pulse number of 24, only the harmonics of the orders 23, 25, 47, 49, etc., remain.

As certain harmonics disappear, the relationship between the r.m.s. value of the fundamental of the a.c. current and the total r.m.s. value improves, i.e. increases. This relationship appears in the definition of the power factor λ of a mutator installation under the well-known term of "distortion factor v", namely:

$$\lambda = v \cos \varphi \tag{1}$$

The validity of this equation is strictly limited to supply voltages with a sinusoidal wave-form. When several mutually dephased sets are banked in the manner described the displacement factor $\cos\varphi$ does not vary. On the other hand, the distortion factor v and consequently the power factor $\lambda = v \cos\varphi$, measured at the a.c. terminals of the separate six-anode mutator sets comprising the bank, is somewhat lower than when the total current of a multipulse installation is measured, on account of the increased harmonic content. Depending on the degree of overlap of anode currents when operating at rated current, the difference between the two values of power factor can be as much as 3%. In calculating for a mutator bank with a low pulse number the, for practical purposes, more important displacement factor $\cos\varphi$ from measured readings, it is essential not to use the well-known relationship

$$\lambda = v \cos\varphi = \frac{\text{Effective power}}{\text{Apparent power}} = \frac{P}{S} \tag{2}$$

but rather the formula

$$\cos\varphi = \frac{\alpha_1 + \alpha_2}{2\sqrt{\alpha_1^2 - \alpha_1\alpha_2 + \alpha_2^2}} \tag{3}$$

using the wattmeter deflections α_1 and α_2. In this equation the influence of harmonics on the r.m.s. value of the current vanishes, whereas it is retained in (2), which therefore produces lower resultant values. If the modest improvement in distortion factor is still welcome when the pulse number is raised from six to twelve or twenty-four, it in no way compensates in itself for the expense of increasing the pulse number.

Therefore, from the point of view of the actual mutators there is no inducement to raise the pulse number above six (or at the very most twelve).

Effects of Increased Pulse Number

The full effect on the harmonic content of both a.c. current and d.c. voltage of increasing the pulse number is only felt under certain conditions. In multipulse installations (e.g. twelve) where the d.c. currents of individual six-anode sets are in parallel, it is an accepted fact that an extraneous voltage harmonic of low order (say 5th or 7th order) present in the primary a.c. system may cause considerable inequalities in the current output of the individual six-phase sets [4]. Whether this inequality is allowed to remain or whether it is suppressed by appropriate modification of the grid control of the sets, the full compensation of low-order harmonics in the primary and d.c. currents, originally visualized by increasing the pulse number, will in both cases be more or less disturbed, in other words: instead of pure multipulse operation, the result is a mixture in which a sometimes appreciable portion of the undesirable low-order harmonics remains uncompensated in spite of the increased pulse number. This occurs frequently to a greater or lesser degree.

It is easy to see that the amount of external compensation of certain groups of harmonics visualized in increasing the pulse number can only be attained when the vector sum of the harmonic currents of that particular order is zero for the entire mutator installation. If, for instance, one six-phase set becomes inoperative due to a disturbance, then immediately all the harmonics produced by that set in the a.c. and d.c. sides reappear. A similar effect is observed when the loading of one or more six-phase sets is reduced or when the grid voltages of individual sets are unequally regulated.

Through the natural distortion of the a.c. voltage by a mutator installation with a low pulse number, it is also possible, in a roundabout way, to adversely affect, for example, the current distribution of the mutually dephased six-anode sets of a bank of mutators. Natural distortion, as will shortly be explained, varies with the current.

Distortion of the Supply-Voltage Wave

Distortion of the voltage wave-form in a supply system can be due to a variety of causes. In general, the voltage supplied to a mutator installation at no-load already exhibits a certain amount of distortion. As the mutators are loaded, additional distortion, proportional to the load, becomes noticeable. To distinguish between the two conditions, the first will be referred to as external distortion, the second as natural distortion. The influence of external distortion has already been described elsewhere [4]. The present article will confine itself mainly to natural distortion.

The natural distortion of the primary voltage by a mutator set is the result of resistive and above all inductive voltage drops caused in the impedances of the a.c. supply system by harmonic currents absorbed by the mutators. Inseparably linked with this a.c. voltage distortion is an additional drop in the d.c. output voltage of the mutators, which is proportional to the current [5]. Here, to a first approximation, the resistive losses are negligible. If no capacitances are present, the individual harmonic portions of the total distortion voltage are proportional to the harmonic current and the reactance of the supply system. In accordance with a previous argument, increasing the pulse number of the installation reduces the harmonic content of the total a.c. current and thus simultaneously the natural distortion of the a.c. voltage.

System impedance denotes the resultant impedance of all those parts of the system in which the harmonic currents of the mutators flow. For the present investigations the mutator installation must be treated as the origin of the harmonics, producing harmonic currents proportional to the loading; for these currents the generators supplying the system may be considered as connected in parallel with all other consumers. This means then that in addition to the impedances of the generators, transformers and transmission lines feeding the system, all the shunt-connected impedances of the current-consuming equipment, such as motors and heat producers, within the system, are also included. This resolves to the known fact that, for negligible capacitance, it is not the actual full surge reactance of the system, referred to the a.c. terminals of the mutator bank and corrected for harmonic frequency, that is the effective reactance for the current harmonics of the mutators. Actually, the lower the line impedance between mutators and other current-consuming equipment and the greater the connected load, the smaller the proportion of surge impedance which should be included.

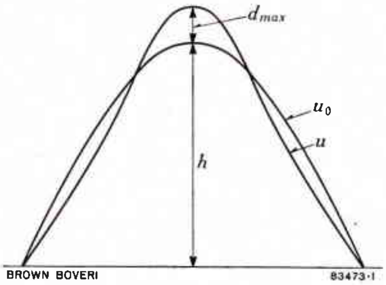


Fig. 1.—The percentage distortion v_u of the voltage curve u is defined by the relation $v_u = 100\, d_{max}/h$

u = Voltage curve
u_0 = Fundamental of u
d_{max} = Maximum deviation of curve u from fundamental u_0
h = Amplitude of fundamental u_0

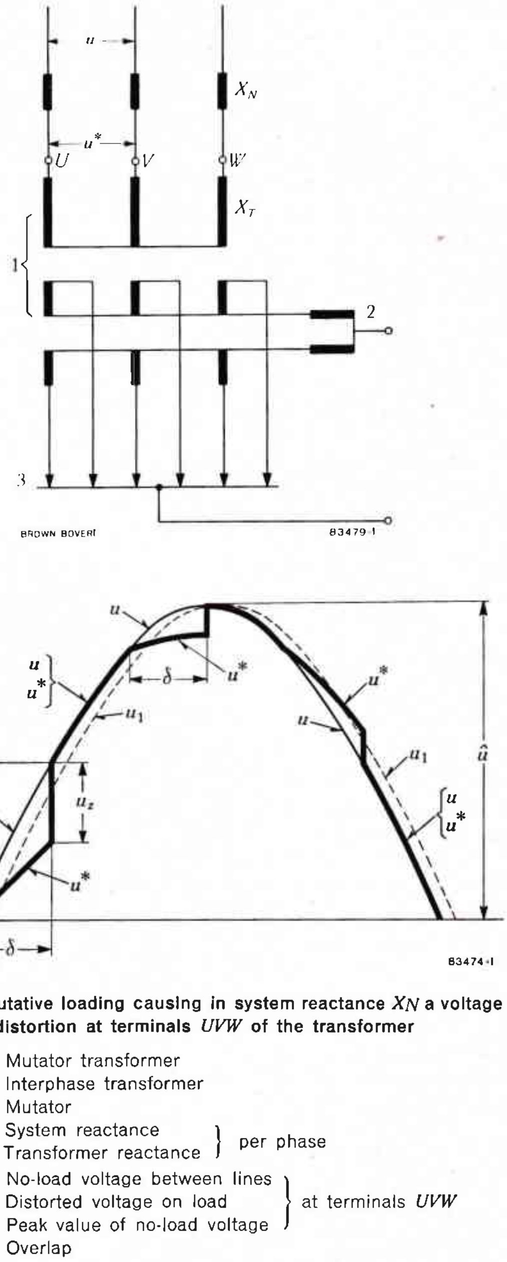


Fig. 2.—Mutative loading causing in system reactance X_N a voltage distortion at terminals UVW of the transformer

1 = Mutator transformer
2 = Interphase transformer
3 = Mutator
X_N = System reactance } per phase
X_T = Transformer reactance } per phase
u = No-load voltage between lines } at terminals UVW
u^* = Distorted voltage on load } at terminals UVW
$\hat{u}$ = Peak value of no-load voltage } at terminals UVW
δ = Overlap
u_z = Maximum surge of distorted curve u^*
u_1 = Fundamental of distorted curve u^*

Thus as the ratio of the power of a mutator bank to the total connected power of the generators increases, not only does the absolute harmonic current rise, but simultaneously also the resultant system impedance, due to the loss of a part of the "shunt" circuit through the remaining current consumers. The true surge reactance of the system is therefore less than normally assumed.

When planning a large mutator installation, a certain insight into the distortion to be expected in the supply voltage at the a.c. terminals would help in choosing the total number of phases. This requires the establishment of a mathematical relationship between P_g, the d.c.

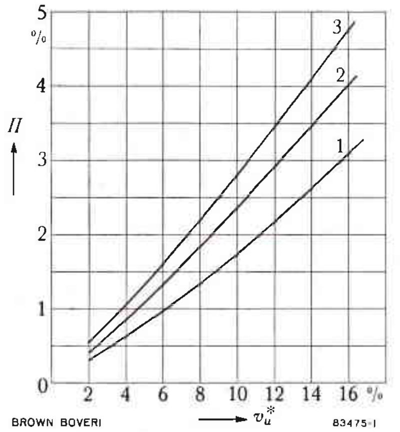


Fig. 3. — Percentage ratio Π of the six-phase limiting power as a function of the tolerated distortion v_u^* in the supply voltage of a mutator installation

1 = Percentage limiting power for $\varepsilon_c T = 5\%$
2 = Percentage limiting power for $\varepsilon_c T = 10\%$
3 = Percentage limiting power for $\varepsilon_c T = 15\%$
$\varepsilon_c T$ = Percentage transformer impedance voltage

power of the installation; P_{cN}, the surge power[1] of the system; ε_{cT}, the percentage transformer impedance voltage; and u_z, the permissible surge in the supply voltage at the a.c. terminals. In addition a theoretical definition of distortion v_u has to be used, which must bear as simple and clear a relation to the other quantities as possible. In this respect it is not suitable to adopt the definition according to Fig. 1 (maximum deviation of the curve from its fundamental as a percentage of its amplitude), because the position of the fundamental itself is different again from the undistorted no-load curve. Since it is mathematically too complicated, the definition of distortion as the total r.m.s. value of the harmonics as a percentage of the r.m.s. value of the fundamental is equally unsuitable. From the character of the distortion of the a.c. voltage, which as illustrated in Fig. 2 is due to six-pulse mutators, it can be seen that the maximum transient voltage u_z, occurring at the moment of extinction of the anodes of a secondary phase, i.e. at the end of commutation, measured as a percentage of the peak value of this voltage, is a direct and practical expression for the natural distortion v_u^* of the curve. Whereas for a pulse number $p = 6$ the transient voltage still bears for the most part an asymmetrical distribution in relation to the fundamental curve, as the pulse number is raised and the distortion extends along the whole curve, it also becomes increasingly symmetrical to the fundamental. At $p = 18$ the deviation of the distorted a.c. voltage from its fundamental has already fallen by half.

An approximation, sufficient for practical purposes, shows that the distortion v_u^* is determined by the pulse number p, the power ratio[2] $\Pi = 100\, P_g/P_{cN}$ and the impedance voltage ε_{cT} of the transformer. In Fig. 3, for $p = 6$, the required power ratio is plotted against the tolerated distortion v_u^*, with the impedance voltage ε_{cT} of the transformer as parameter. From this it will be seen, for instance, that with a 10% impedance voltage and 10% distortion, the power ratio may not exceed 2·4%, or in a six-anode mutator set with an output of, say, 4 MW and 10% distortion, the surge power of the system has to be about 170 MVA. In accordance with expectations, as distortion v_u^* and transformer reactance ε_{cT} increase, so, too, does the power ratio Π. In Fig. 4, distortion v_u^* is plotted against pulse number p, for the particular case of $\varepsilon_{cT} = 10\%$, where Π as parameter is between the limits $1\% < \Pi < 16\%$. The distortion curves shown in Fig. 4 should be treated as upper limits in the sense that values occurring in practice will always be less than those given by the curve. Corresponding to the statement that where

[1] The surge power is $\sqrt{3}$ times the product of the rated voltage and the r.m.s. value of the alternating component of the short-circuit current at the start of a three-phase short circuit at the point in the system under consideration.

[2] If for example the a.c. system supplying a mutator installation with a power rating of 4 MW is fed by a transformer rated 40 MVA with an impedance voltage of 10%, including the system reactance on both sides, the percentage power ratio Π is then given by:

$$\Pi = 100 \frac{4 \times 10}{40 \times 100} = 1\%$$

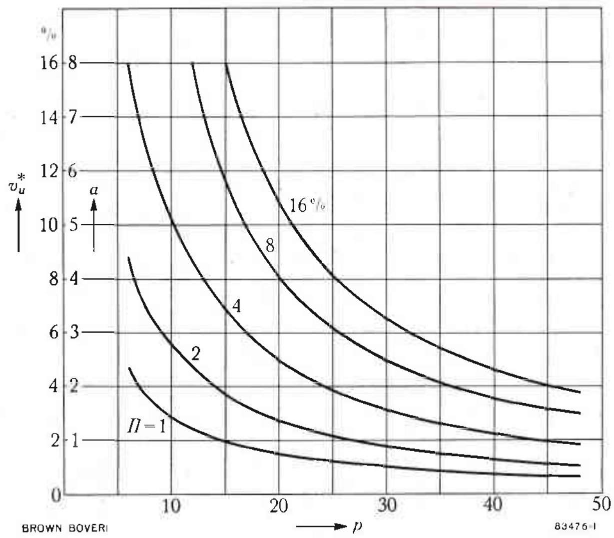


Fig. 4. — Showing how the inductive natural distortion of the supply voltage diminishes with increasing pulse number

v_u^* = Percentage natural distortion of primary voltage
a = Percentage deviation from fundamental
p = Pulse number
Π = Tolerable power ratio
$\varepsilon_c T$ = Percentage impedance voltage of transformer = 10%

the pulse number $p \geqq 12$, the percentage deviation of the curve from its fundamental—as more frequently adopted in investigations of this kind—is only half as large as the value defined above, this deviation a is also included as ordinate in Fig. 4. Hence from the curves, to maintain a given distortion v_u^* with increasing power ratio Π, the pulse number p must also be raised. As long as Π does not numerically exceed a few per cent, the distortion is negligible for low pulse numbers. As the power ratio approaches 16%, a special condition is reached where, for example, a hydro-electric station feeds a mutator installation direct and is thereby fully loaded. With the station fully utilized, this ratio can rise still higher, if between the primary terminals of the mutator transformer and the generator busbars, additional reactances are inserted in the form of transformers or transmission lines, which reduce the relative surge power of the system below the possible maximum value. It is obvious from Fig. 4 that when the power ratio is high and distortion small, a high pulse number should be chosen. It is unreasonable and incorrect, however, to attempt to fix the required pulse number on the basis of the power of the mutator installation. From the aspect of d.c. voltage distortion, too, pulse numbers higher than twenty-four are only justified on very rare occasions.

Too much importance should not be attached to the distortion of the a.c. voltage curve. It is known that the duty or method of operation of that proportion of all current consumers in the system, which from the point of view of power consumption, can be considered as the preponderant section, is in any case only appreciably disturbed, if at all, by relatively large distortions of the voltage curve. Distortions of over 10% frequently occur without an adverse effect being observed. These relationships only cover one aspect of the problem and, particularly when too small values are accepted for the permissible voltage distortion, lead to inappropriate conclusions being reached in respect of the choice of pulse number. From these considerations it is simply concluded that, as regards distortion in the supply voltage, the pulse number for high-power mutator installations must be fixed at 12 to 24 and only in exceptional cases at 36. The illustrated relationships are only valid on the assumption—and this is particularly emphasized—that there are no capacitances present in the a.c. system likely to lead to resonance phenomena. This condition is frequently not fulfilled. Then the unintentional paralleling of capacitances and inductive arms within the system itself can lead to the resonance of certain harmonic currents [6]. In such cases the reactance at certain points in the system is no longer proportional to the frequency by far and the harmonic currents forcibly imposed on the system by mutators can easily lead to extremely large distortions of the supply voltage. These distortions vary with the power factor, system impedance and magnitude of the harmonic currents and are thus variable with respect to both time and position. Imagine, for example, a lumped capacitance at the point in the system under consideration, taking the form of a bank of capacitors with the capacitance C per phase and reactive power rating P_1 for power-factor correction. At this point then, as defined above, due to the apparent inductance L per phase and the pre-determined surge power P_{cN} of the system, a more or less clearly defined current resonance can appear in one harmonic; its order n_r is obtained, to a rough approximation at least, by conversion from the well-known equation

$$n_r^2\, \omega^2\, LC = 1 \text{ whence } n_r = \sqrt{\frac{P_{cN}}{P_1}} \tag{4}$$

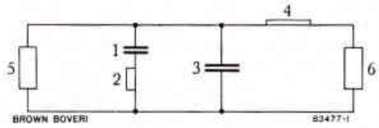


Fig. 5. — Current resonance suppressed by parallel connection of a voltage resonance circuit

1 = Capacitor } Voltage resonance circuit
2 = Choke
3 = System capacitance } Current resonance circuit
4 = System inductance
5 = Mutator
6 = Supply system

It is clear that even an approximation to such resonance conditions can lead to intolerable distortion of the a.c. voltage. On the other hand, the development of this distortion is appreciably diminished by high-power thermal current-consuming plant. A possible remedy is to short-circuit the current resonance circuit by connecting one or two voltage resonance circuits in parallel with it and thus rendering it harmless (Fig. 5).

Synchronous Machines

The harmonic currents flowing to a mutator set produce additional heat in synchronous machines in the circuit, regardless of whether such machines are operating as generator, motor, or synchronous capacitor. Firstly, the harmonics flowing in the stator windings, particularly in the coils near the rotor, can be the cause of increased losses; in addition the stator-current harmonics induce elliptical rotating magnetic fields in the rotor [6]. Compared with the rotor their frequency is 6, 12, 18, etc. times the

supply frequency, whereby the six-fold frequency of this rotating field is produced by the 5th and 7th order harmonic currents together, the twelve-fold by the 11th and 13th order harmonics, and so on. By suppression of, for instance, the harmonic group 5; $7 = 6 \pm 1$, the rotating field with the six-fold frequency in the rotor can be suppressed. The additional heat produced in the rotor by these rotating fields is of a very similar nature to that caused by asymmetrical, single-phase loading of the machine, where, however, as a result of still higher frequencies, the skin effect and the additional losses in the rotor core and damper winding become even more pronounced. Thus the known permissible single-phase load of a machine becomes a concept, but only in very rough relative terms, of the permissible harmonic loading [7]. When the machine carries exclusively a mutative load (i.e. a load due to mutators), the magnitude of individual harmonics decreases at a more than inversely proportional rate as the order increases. Thus suppression of the lower-order current harmonics provides effective thermal relief for the machine. In keeping with a previous statement, in cases where the mutator load on a machine becomes preponderant, the pulse number of the mutators must be made more than 6, so that the high currents of low-order harmonics just disappear. In other words: The permissible mutative proportion of the total load on the generators increases with the pulse number. When mutators form the load exclusively, the pulse number of the installation must be fixed, according to the output and type of machine, at six to twelve for salient-pole machines and twelve to twenty-four for smooth-core (turbo-) machines. Otherwise there is a risk of local overheating of the pole shoes, the damper winding, or the rotor end-bells of turbo-machines. When installing synchronous machines, especially turbo-machines, in close proximity to high-power mutator installations it is always advisable to determine the probable harmonic load on the machines and to make due allowance in their design. If the pulse number of the mutators can be freely chosen, this number and the design of the generator must harmonize with each other. For nearly all cases 12 to 24 phases are quite adequate. With a high mutative load and both smooth-core and salient-pole machines in parallel on the a.c. side it should be borne in mind that the smooth-core machines not only take up a greater proportion of harmonic currents, but at the same time exhibit a greater degree of sensitivity.

In summing up, it may be said that the generators, although an important part of the system, give no grounds for raising the pulse number of large mutator installations above 24.

Induction Motors

The armature of the induction motor is designed to carry alternating currents in any case. Practical observations show that intolerable excess heating in the rotors of such machines by harmonic currents originating in mutators are not to be expected, even under the most unfavourable circumstances; the influence of induction motors on the choice of pulse number can therefore be ignored.

Capacitors for Power-Factor Correction

If power-factor capacitors are connected in parallel with a mutator installation, then obviously the "softer" the system, i.e. the lower its surge power at the point in question, the greater the proportion of harmonic currents which will flow through the capacitor bank. The additional heating of the capacitors through increased losses due to harmonics is, however, proportional to the sum of all the products of voltage and current of each separate harmonic. As long as there is no approach to current resonance, as already described in the paragraph on the effects of increased pulse numbers, these additional losses in the capacitors are mostly insignificant, especially as the capacitors are usually designed to take into account the possibility of heavy harmonic current loads.

Meriting particular attention is the case already mentioned, in which the capacitor impedance for a certain current harmonic and the system impedance approach resonance. Then the voltage and current of one or two adjacent harmonics in the capacitors can reach quite intolerable values. In multi-phase mutator banks, this resonance can lead not only to gross asymmetry in the current distribution between the various mutually dephased six-anode sets of the bank, but also under certain conditions to overheating proving deleterious to the capacitor. Depending on the loading and state of the system at a particular hour of the day, such conditions can appear and disappear again. Suitable remedial methods have already been described.

Earth-Fault Neutralization by Arc Suppression Coils

It is well known that in transmission lines and cables, earthed via arc suppression coils, a large distortion in the supply voltage may cause the fault current to deviate from the sine-wave form with the result that it cannot be sufficiently neutralized by the coil. This distortion of the fault current can just as easily have an unfavourable as a favourable effect on the neutralizing properties of the coil.

Consideration of this problem appears to have merited only very occasional attention, so that this disturbance, where originating in mutators, is of no great significance.

D.C. Systems fed by Mutators

The pulse number of a mutator substation feeding a d.c. network affects the ripple of the d.c. output voltage in much the same way as it does the harmonic content of the a.c. input current: the higher the pulse number the less the ripple in the voltage. Even the normal pulse numbers six and twelve cause a voltage variation of only a few per cent, which is acceptable for most purposes. Should it be unacceptable, for instance in a traction system with telecommunication lines running parallel, the pulse number could be raised. For reasons to be given in the following paragraph, this would be relatively expensive and, under certain conditions, only partially effective; a pulse number of more than 6 or 12 is therefore ruled out. Moreover, according to the circumstances, the cause of the disturbance could be overcome by incorporating filters in the d.c. network or laying the telecommunication lines underground.

Other Effects of Harmonics

The effect of harmonics on a.c. meters employing the Ferrari disc principle and on telemetering and remote supervisory systems is well known, as, too, are the available counter-measures. There is therefore no need to discuss them further here.

Interference to Communication Lines

The harmonics in the voltage and current carried by a high-voltage transmission line can, in certain circumstances, have an adverse effect on neighbouring communication lines [8]. Noise in telephone circuits is most serious in the frequency range of 1000 to 1200 c/s. If, bearing this fact in mind, the main interference frequencies of harmonics produced by mutators were required to be suppressed, the pulse number of the latter would have to be made at least 30. Now, apart from these harmonics, h.v. lines are responsible for other, far more serious interference which results from inadequate symmetry between the two systems, especially when conditions in the h.v. line are abnormal (earth faults, short circuits). Even if the pulse number of large mutator installations were made 30 or more, the interference due to h.v. lines would only be partially overcome. These facts, coupled with considerations of atmospheric interference and the ever-increasing electrification of built-up areas, make it almost compulsory to lay important long-distance public telephone circuits underground, thus avoiding nearly all the interference effects mentioned above.[1] Moreover, on the communications side there are simple and effective means in existence, which can reduce possible interference from h.v. lines to tolerable proportions.

Consideration of communications interference, therefore, does not warrant the pulse number of large mutator banks being raised any higher than is necessary for other reasons.

Conclusions

The final outcome of these investigations is that, in general, individual mutator sets should be made six-phase, in exceptional cases twelve-phase at the most. Even under extreme conditions, the important parts of a supply system are not likely to be affected by the operation of mutators to a degree sufficient to warrant pulse numbers higher than 12 or 24; in extreme cases 36. Conversely, high pulse numbers are no certain safeguard against voltage distortion due to current resonance. As far as the influence on over-head telephone lines of h.v. lines feeding mutators is concerned, there are other sufficiently important reasons for going underground, particularly for long-distance circuits; the field of telecommunications can therefore provide no important arguments for increasing the pulse number of mutator installations.

In these circumstances then, it is a waste of time to attempt to enforce a general, rigid ruling as to the correct choice of pulse number, more especially where the demand is for numbers higher than 24. Corresponding to the wide variety of operating conditions and the requirements of such installations, the pulse number can only be decided by treating each case on its merits.

MS 819 (KME) *E. Kern*

[1] International recommendations for telecommunications prescribe that the r.m.s. value of the e.m.f. induced in a branch of a communication line by faults (short circuits, etc.) in h.v. lines, should not exceed 430 V. With the usual high surge power of systems and where the lines run parallel to each other, this recommendation implies either the adoption of impracticably large clearances between lines or laying the communication cable underground. This is a reliable means of eliminating all harmonic interference originating in mutators.

Bibliography

[1] E. Fässler: Die Stromoberwellen auf der Wechselstromseite von Stromrichtern. Arch. Elektrotech. 1938, Vol. 32, No. 10, p. 640–54.

[2] E. Fässler: Der Einfluss von Oberwellen im Drehstromnetz auf die Harmonischen der Gleichspannung und des Netzstromes von Stromrichtern. Arch. Elektrotech. 1940, Vol. 34, No. 4, p. 209–29.

[3] E. Fässler: Ein Streifzug durch die netzseitigen Spannungen und Ströme von Mutatoren. Bull. schweiz. elektrotech. Ver. 1946, Vol. 37, No. 23, p. 677–88.

[4] M. Hürlimann: Connection and Number of Phases of A.C.-D.C. Mutator Plants with Special Regard to the Harmonics in the Direct Voltage and Primary Current. Brown Boveri Rev. 1947, Vol. 34, No. 10/11, p. 200–8.

[5] E. Kern: Die Messung des im Wechselstromnetz auftretenden zusätzlichen Spannungsabfalles in Mutatoranlagen. Bull. schweiz. elektrotech. Ver. 1937, Vol. 28, No. 9, p. 183–5.

[6] L. Lebrecht: Stromrichterbelastung der Hochspannungsnetze. Elektrotech. Z. 1935, Vol. 56, No. 35, p. 957–60 and No. 36, p. 987–90.

[7] R. Pohl: Belastbarkeit von Generatoren bei Betrieb auf Stromrichter. Elektrotech. u Maschinenb. 1935, Vol. 53, No. 17, p. 193–6.

[8] R. Rüdenberg: Elektrische Schaltvorgänge. 3rd Ed., p. 463–74 and 614–15. Springer, Berlin 1933.

RECENT VACUUM PHYSICS INVESTIGATIONS IN THE MUTATOR FIELD

621.314.65:533.5

The development of pumpless steel-clad mutators, the steadily increasing demands being made on pumped mutators, and finally the rationalization of production methods necessitated a new series of investigations into mutator vacuum phenomena. In the main the experiments centred round intensifying and accelerating the process of evacuation, improving and maintaining the tank seal, and reducing the residual gas pressure in the mutator both during formation and service. The author gives a short description of some of these investigations.

MERCURY-ARC mutators can only operate reliably when their internal pressure remains within certain limits. If it is too high, the rate of anode disintegration will increase, with the well-known and unwelcome accompanying phenomena, while with increasing pressure the greater will be the risk of back-fire. The internal pressure is the sum of the pressures of the mercury vapour and permanent residual gases. The mercury-vapour pressure is to a large extent governed by the temperature of the envelope, and can be maintained within the permissible limits by means of an appropriate regulating system. The residual gas pressure is determined by the state of equilibrium set up between the gases or vapours finding ingress through leaky seals or evolved by the inner surfaces and those evacuated by the vacuum pump or consumed by the arc. It has already been demonstrated in the pages of this journal that the residual pressure in a mutator should be as low as possible [1].[1] This can be achieved, firstly, by degassing the internal parts as far as possible, secondly, by ensuring that all seals are adequately vacuum-tight and, thirdly, by using an efficient pumping system with the least possible pressure drop in the tubes. The significance of these points grows as the output of the mutator is increased.

Developments in the last few years necessitated experiments in this field, the results of which are described in the following pages.

[1] The figures in brackets refer to the bibliography at the end of the article.

Investigations into the Mutator Degassing Process

Before assembly, every component part of a mutator contains some gas or vapour occluded in it or adsorbed on its surface, originating partly in the manufacturing process and partly in the surrounding vapour or gas from which traces are later absorbed by the component. When the mutator is evacuated these gases and vapours are liberated. This evolution process (desorption) is intensified and accelerated when the components are simultaneously heated, either from an external source or by an electric current.

The following table lists the gas contents of the most important materials used in mutator construction. When the interior of the mutator is completely degassed to a pressure of the order of 1 mTorr the volume of liberated gas is several hundred thousand times that at atmospheric pressure as shown in the table.

Gas Content of the Most Important Mutator Materials

Material	Gas content at 760 Torr		Measured by
	cm^3/kg	$cm^3/100\ cm^3$	
Steel	70–700	55–550	Norton and Marshall [2]
Graphite not pre-treated	270 +	60 +	Norton and Marshall [2]
not pre-treated	900	200	Brown Boveri
degassed	1·5–12	0·3–2·7	Norton and Marshall [2]
degassed	13	2·9	Brown Boveri
Rubber	3500	435	Brown Boveri

The gases liberated into the discharge space of the mutator by the processes of evacuation and heating would cause a considerable rise in pressure, if they were not removed by constant pumping.

When mutators were in their infancy, this degassing process used to take several days or even weeks; in the interim the development of more efficient vacuum pumps has enabled this period to be substantially reduced. Efforts are now being made to speed up the process still further, for which the following methods may be adopted:

1. Minimizing the diffusion distances by reducing the thickness of components, especially the anodes.
2. Raising the temperature limits of internal parts during formation (since the higher the temperature, the more rapid will be the processes of diffusion and gas evolution).
3. Increasing the efficiency of the evacuation equipment still further by using pumps with a higher pumping speed and tubes with a lower pressure drop.
4. Thorough cleaning and preliminary degassing of all component parts.
5. Using new materials with a lower gas content.

Today, all these methods are being employed simultaneously, with the result that degassing is not only quicker, but also more thorough. The value of this is appreciated later during the first weeks or months of service when the risk of back-fire on overloads or short circuits, due to gas evolution—particularly from the anodes—is reduced.

Supervision of Degassing Process
Low-Pressure Gas-Flow Meter

To keep losses small, a mutator is usually formed at a low phase voltage with a pre-determined current schedule. This is set up in such a manner that the pressure inside the mutator is prevented from exceeding a certain value during the entire formation process. Experience has shown, however, that mutators of identical design and produced in the same way behave differently as far as gas liberation is concerned, so that formation cannot always be carried out to a rigid schedule. It could of course be arranged always to raise the current so slowly

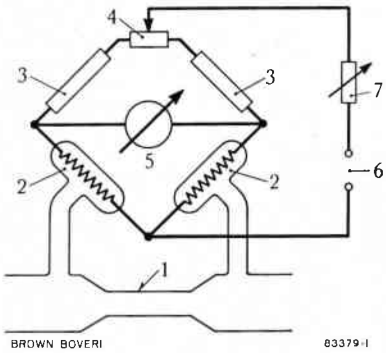


Fig. 1. — Basic connections of the gas-flow meter

1 = Throttle tube
2 = Hot-wire vacuum gauge
3 = Resistor
4 = Zero-setting potentiometer
5 = Indicator
6 = D.C. source
7 = Resistor for heating-current adjustment

that even in the worst case—where a mutator is very gassy—the vacuum would remain within tolerable limits. But then the requirements for economical formation would not be fulfilled, at least not in every case.

Furthermore, it has been demonstrated that merely checking the state of vacuum is not sufficient to obtain satisfactorily formed mutators, especially when the vacuum meter is nearer to the pump than to the mutator. The Company therefore decided first for pumpless, later for pumped mutators, to measure the gas evolved at all stages of the forming process, and adapt the current increase to the state of desorption. At first the process involved trapping the liberated gases between the high-vacuum and backing (preliminary-vacuum) pumps and to measure the rate at which the pressure increased. From this and the known volume of the trap it was possible to determine the amount of gas liberated per unit of time. This method is complicated and tedious. A gas-flow meter has therefore now been developed which functions automatically, and continuously records the amount of gas liberated in the mutator. The principle on which it works (see Fig. 1) is that between the high-vacuum and backing pumps there is a throttle tube in which the pressure drop is measured by hot-wire vacuum gauges. Over a wide range this pressure drop is a specific function of the quantity of gas flowing. The two vacuum gauges provided are each connected in one arm of a bridge and are mutually adjusted until they balance when no gas is flowing through the throttle tube. By selecting tubes of appropriate dimensions and suitable resistance elements it is possible to arrange for the balance to be definitely disturbed even by quite small quantities of gas, and to

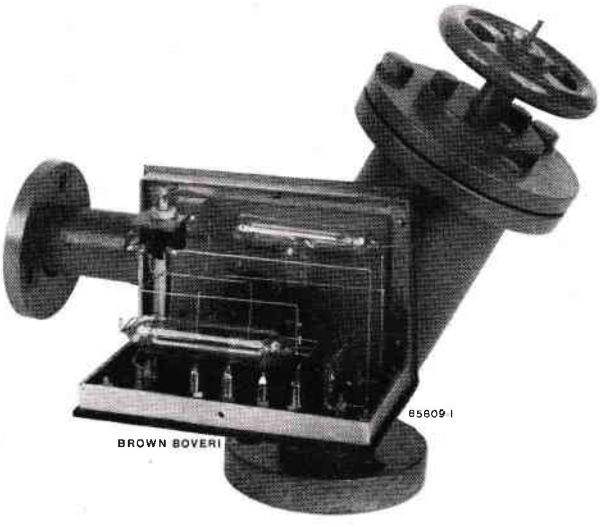


Fig. 2. — Gas-flow meter with adjustable throttle tube to extend the range of measurement

The instrument is shown with the cover removed.

obtain easily measurable deflections on a recording or indicating instrument. The range of measurement can be extended by adjustment of the throttle tube. Fig. 2 illustrates a practical version of the gas-flow meter.

As the response of the hot-wire instrument varies from one type of gas to another, it is essential that a calibration curve be prepared for each gas. It has been proved, however, that the response with the gas mixture given off by mutator parts is much the same as that with air. The flow meters developed by Brown Boveri are calibrated to obtain a reasonable reading down to 1 mTorr.l/s, although this is by no means the lowest possible limit.

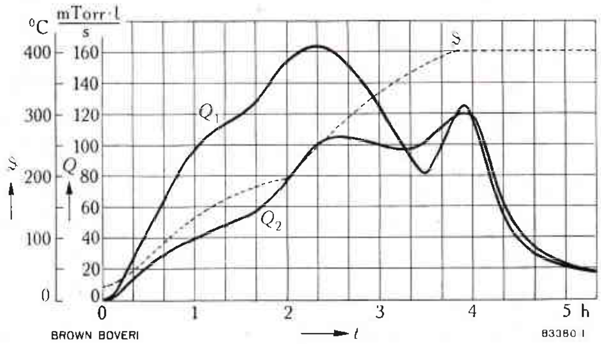


Fig. 3. — Initial evolution of gas when two identical pumpless mutators were heated

ϑ = Oven temperature in °C
Q_1, Q_2 = Gas evolution (in mTorr.l/s)
t = Time in h

The first high peak is due to the evaporation of the film of water on the inner walls and from slight impurities. The differences between curves 2 and 3 are governed by the different degrees of cleanliness of the inner surfaces. This shows the importance of cleanliness during manufacture from the point of view of the degassing process.

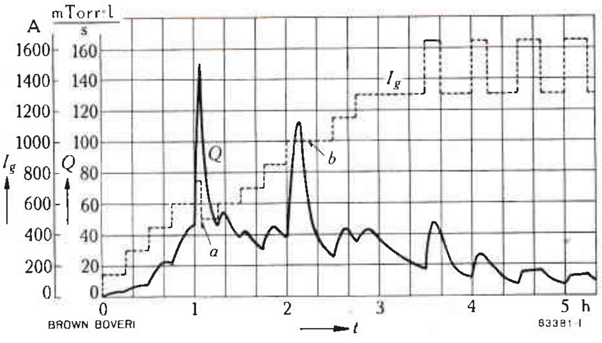


Fig. 4. — Initial evolution of gas during formation of a pumpless mutator by electric current

I_g = D.C. current in A
Q = Gas evolution (in mTorr.l/s)
t = Time in h

At point *a* the current had to be reduced due to excessive gas evolution; at point *b* the raising of the current was delayed due to excessive gassing.

The progress of the degassing process can be followed quite easily with the help of this flow meter and it is a simple matter to decide when to stop. Fig. 3 shows the initial rate of gas liberation as recorded on the charts of the gas-flow meter when two identical pumpless mutators are heated. Fig. 4, on the other hand, shows the same reading when a similar mutator is formed by passing electric current through it. Both cases were special examples selected for their illustration value.

The gas-flow meter proved extraordinarily useful in the experimental investigations into the gas evolution from the materials used in mutators. It enabled important conclusions to be drawn as to the nature and duration of preliminary degassing and the storage of preliminarily degassed parts.

The Mutator Sealing Problem

Development of New Seals

Merely to drive out as much gas and vapour as possible during the formation process does not suffice to keep the residual gas pressure at a low level when the mutator is later in service. To achieve this, good seals are also essential between individual parts of the envelope and the electrode bushings.

The question of the sealing of mutators seemed to have been solved years ago. However, new problems became evident, firstly, when the construction of pumpless mutators was commenced and, secondly, through continually increasing the thermal demands on the seals of the pumped type—particularly those with air-cooled tank. In pumped mutators, natural rubber was the most popular sealing

material for bushings and vacuum tubing. For some time now synthetic rubbers have also been utilized. While natural rubber has the quality of low gas evolution, synthetic is generally more resistant to heat. Practical experience has indicated that for seals, one side of which is in contact with air, the temperature should not exceed 120 °C with synthetic and 80 °C with natural rubber. In many cases, though, it is desirable to have a material which will stand up to 150–180 °C without changing or liberating large amounts of gas. The evolution of gas during formation can be appreciably reduced if the material is degassed prior to its incorporation in the mutator. However, nothing can be done to improve the resistance to heat.

In the search for new materials for high-temperature seals, investigations were first carried out using metal rings. These were confined to steel, as many other metals are attacked by mercury vapour. First of all a knife-edge seal was developed to connect pumpless mutators to the pumping system during formation; this was capable of withstanding temperatures of 400 °C and could be dismantled frequently. Subsequently, using flat, octagonal soft-annealed steel rings up to 300 mm diameter, seals were produced which could be heated again and again up to 400 °C and still remain vacuum-tight. To check for vacuum tightness at room and higher temperatures a helium leak detector with a sensitivity of 10^{-5} mTorr.l/s and operating on the principle of the mass spectrometer, was used.

Seals of the type mentioned demand a high degree of accuracy in production; furthermore, they are very delicate and can easily be damaged during assembly. The high bolt pressure required is also a disadvantage. Attention was therefore directed to softer materials, and Teflon proved to go a long way towards fulfilling the requirements, i.e. minimum gas evolution in vacuo, and stability up to at least 150 °C. Its only drawback is a slight tendency to creep under pressure at high temperatures. Fig. 5 shows a section through a double Teflon-mercury seal.

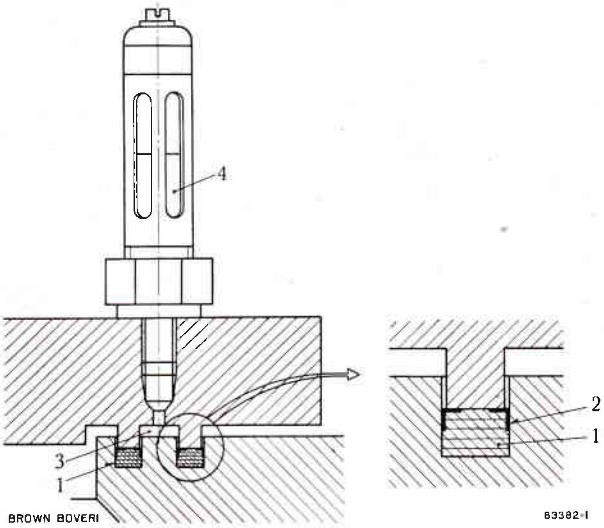


Fig. 5. — Section through a Teflon double seal

1 = Teflon ring
2 = Washer to prevent Teflon creep
3 = Mercury
4 = Mercury level gauge

Seals with steel washers can be used for temperatures up to 200 °C. Gas evolution still remains very slight at such temperatures.

Testing Seal Tightness

For a long time the only known method of testing for leaks was to subject the tank to an internal pressure above atmospheric. Only the standing test was available to check tightness, this being determined by the pressure rise in a given time. To this method—which although simple is no longer equal to the demands of modern practice—have been added a series of new processes [3, 4]. The best apparatus at the moment is the helium leak detector working on the principle of the mass spectrometer [5] as this uses a gas not normally encountered in the specimen under test and exhibits the greatest sensitivity for all processes. With this detector leaks of the order of 10^{-5}—10^{-6} mTorr.l/s can be measured. If a leak in a pumpless mutator of $\approx 1 \times 10^{-5}$ mTorr.l/s is classed as permissible, then in one of the smaller types having a volume of 50 l, this would result in an annual pressure rise of 6 mTorr. Taking the high rate of gas consumption by the arc [6] into consideration this can be tolerated without further question. The sensitivity of the helium leak detector is thus just sufficient for the task in hand. It should be noted, however, that this sensitivity only applies to leak testing, where the test specimen is completely surrounded by an envelope filled with helium, which can thus cover the whole of the surface for as long as necessary. Should a leak be discovered in this way, pinpointing it by blowing a fine jet of helium at the suspected region can, for two reasons, meet with considerable difficulties. Firstly, helium needs time to penetrate into the test specimen; in the case of long, narrow pores this can take up to several minutes. Secondly, a certain period must expire before the partial pressure of the helium in the test specimen is high enough to be recorded. This

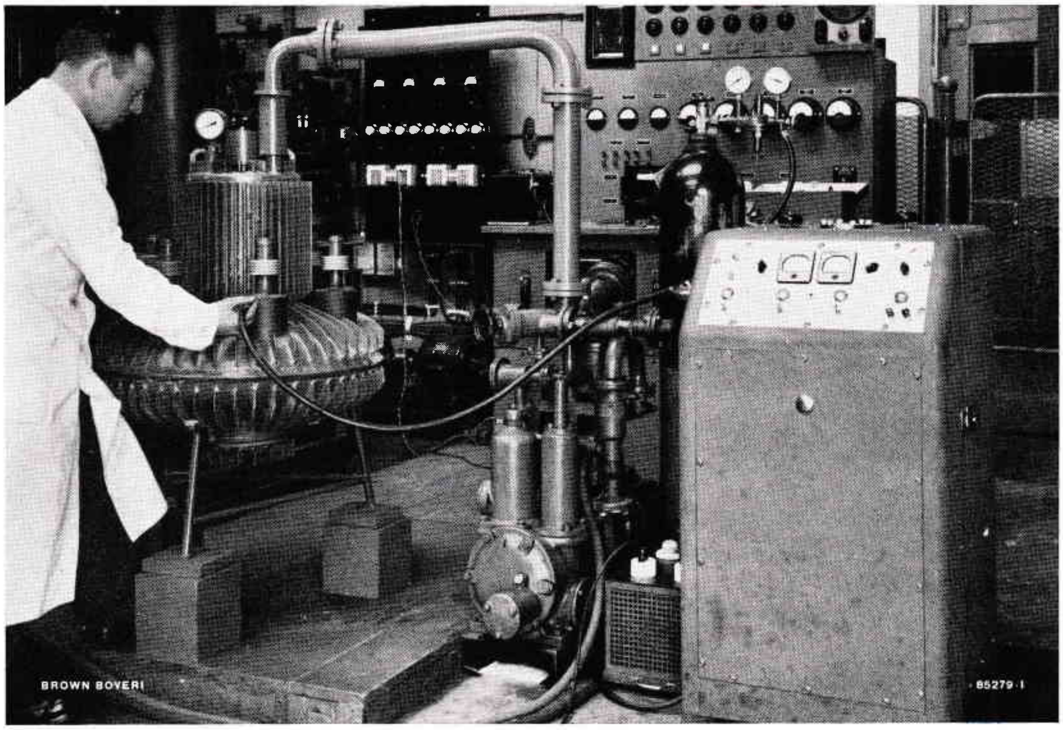


Fig. 6. — Examining a pumpless mutator for leaks with a helium leak detector

On the left is the mutator under test and on the right the detector. Between the two is an auxiliary vacuum pump set to exhaust the mutator; this is shut down during the leakage test.

pressure is given by the equation

$$p = \frac{U}{S}\left[1 - e^{-(S/V)\,t}\right]$$

where U = leakage coefficient; S = pumping speed of the vacuum pump connected to the specimen; V = volume of the test specimen.

When the volume is large the rate of pressure rise will therefore be considerably reduced. An improvement can be effected by inserting the leak-detector between a high-speed diffusion pump and a backing pump, the former being connected to the test specimen. As, however, the mass spectrometer works at a pressure of the order of 10^{-4} Torr, the tube to the leak detector must be throttled, although this tends to reduce the sensitivity of the apparatus slightly. In individual cases, therefore, it is better to arrange the leak detector normally and test ever-decreasing areas of the test specimen by the envelope method until a small surface is found within which the leakage is obviously located and which permits the suspected points to be blown long enough with a helium jet.

Although, in principle, a vacuum container should be tested in vacuo, in particularly difficult cases the opposite method must be adopted. The test specimen is filled with a helium-air mixture at a pressure above atmospheric and the exterior examined for gas egress by a probe coupled to the leak detector.

Fig. 6 illustrates the method of searching for a leak in a pumpless mutator using the helium leak detector. This apparatus is not only extremely valuable for testing assembled mutators, but also for investigating new materials for porosity and for checking seals.

Investigating the Pressure Drop in Vacuum Tubing

In Region between Molecular and Frictional Flow

To produce a sound and lasting vacuum, the rapid extraction of the gases from a mutator during formation must be performed by efficient pumps. As a rule these cannot be coupled direct to the mutator but must be connected by a tube. As a result the evacuation capacity of the pump is rapidly throttled. The importance attached to the pressure drop in the vacuum tubing and the fact that there are no accepted laws by which it can be calculated were considered sufficient grounds for the Company's physicists to carry out their own investigations into this problem.

In unit time the flow of gas through a section of tube is

$$Q = F \Delta p$$

(F = resistance coefficient of the tube; Δp = difference between initial pressure p_1 and final pressure p_2 of tube; $\Delta p = p_2 - p_1$).

In practice the main problem lies in the calculation of the pressure drop occurring in a tube for a given rate of flow per unit time, or of the permissible quantity of gas, also in unit time, to produce a fixed pressure drop. This ends in a definition of the resistance coefficient of the tube.

In vacuum physics a distinction must be made between

(a) flow with external friction or molecular flow and

(b) flow with internal friction or frictional flow

With which of the two one is faced in a particular example depends on the mean free path related to the cross-section of the tube. For tubes with a circular cross-section there is

frictional flow when $\lambda < D/100$, and

molecular flow when $\lambda > D/3$

(λ = mean free path [cm], D = diameter of tube [cm]).

In the region of laminar frictional flow the resistance coefficient can be calculated by using Poiseuille's law; for molecular flow it is obtained from a law deduced by Knudsen. In mutator engineering the most usual region is the intermediate one where

$$\frac{D}{100} < \lambda < \frac{D}{3}$$

For this region Knudsen [7] has supplied the semi-empirical formula

$$F = \frac{\pi}{128}\frac{D^4}{\eta L} p_m + \frac{1}{6}\sqrt{\frac{2\pi k T}{m}}\frac{D^3}{L}\left[\frac{1+\sqrt{\frac{m}{kT}}\frac{D}{\eta}p_m}{1+1{\cdot}24\sqrt{\frac{m}{kT}}\frac{D}{\eta}p_m}\right]$$

where L = length of tube, p_m = mean pressure in tube, k = Boltzmann constant, T = absolute temperature, m = molecular mass, η = dynamic viscosity of the gas.

This law appears to be universally applied for the transitional region. However, several years ago Brown, DiNardo, Cheng and Sherwood [8] demonstrated that it only provides accurate results with glass and copper tubes; with steel tubes the measured values deviated appreciably from the calculation. Theoretical investigations subsequently led to the new law

$$F = \frac{\pi}{128}\frac{D^4}{\eta L} p_m \left[1 + 8\left(\frac{2}{f} - 1\right)\frac{\lambda}{D}\right]$$

($f = \dfrac{\text{Number of diffuse reflected molecules}}{\text{Total molecules impinging per cm}^2\text{ of surface area}}$).

The above authors quote the following values for f:

For glass tubes $\begin{cases} f = 0{\cdot}77 \text{ in low-pressure region} \\ f = 0{\cdot}84 \text{ in higher pressure region} \end{cases}$

For copper tubes $f = 0{\cdot}88$

For iron tubes the term in the square brackets was expressed as a curve. Up to quite high pressures this would give values (not constant) of $f > 1$ which, of course, is not possible. To verify this new law careful measurements were taken using vacuum tubing of various dimensions; these gave the following interesting results:

1. The resistance coefficient as calculated by Knudsen's formula can vary by up to 30 % from the measured values in the case of steel tubes.
2. Theoretically deduced resistance coefficients and pressure drops agree very nearly with measured values when based on the formula of Brown and his co-authors.
3. The definition of f favours the idea that the values of this quantity depend on the state of the inner surface of the tube. The above authors disagree with this view. The Company's measurements have proved, however, that the drop and thereby the coefficient f is slightly lower for polished than for rough tubes. For sand-blasted steel tubes a coefficient $f \geq 1$ should be used; for lightly polished tubes $f = 0{\cdot}95 - 0{\cdot}97$.

Fig. 7 shows how well the calculated and measured values of pressure drops agree for two different tubes.

Vapour Traps in Vacuum Tubing

A low pressure in the vacuum tubing of a mutator can, in certain circumstances, have undesirable consequences, in that—particularly with air-cooled types—mercury vapour can pass from the mutator into the high-vacuum pump or vice versa. This can be counteracted by incorporating vapour traps in the tube, which on the one hand, should allow as little mercury vapour through as possible, but on the other should offer little resistance to the gases

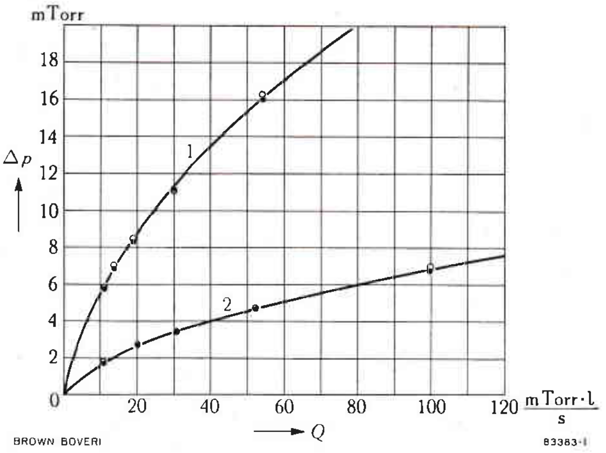


Fig. 7. — Pressure drop Δp in vacuum pipes related to a certain gas flow Q

1 = Tube 28 mm inner diameter, 1000 mm long, interior lightly polished
2 = Tube 39·5 mm inner diameter, 800 mm long, unpolished
● = Calculated points
○ = Measured points

being evacuated. Despite these two conflicting conditions, it has been proved that, by suitable design, both can be reasonably well satisfied. The main consideration is to arrange the baffle plates in such a way that the impinging particles condense on them directly, or are reflected and diverted to cool surfaces.

Simple traps have now been developed which, while reducing the pumping speed of the vacuum plant by no more than 20 %, allow only the merest fractions of one per cent of the mercury vapour to pass.

MS 780 (KME) *F. Grütter*

Bibliography

[1] A. Gaudenzi: Some Causes of Backfires and their Suppression. Brown Boveri Rev. 1938, Vol. 25, No. 5/6, p. 97–8.

[2] F. J. Norton and A. L. Marshall: Trans. Amer. Inst. Mining Met. Engrs 1944, Vol. 156, p. 351.

[3] J. Blears and J.H. Leck: General Principles of Leak Detection J. sci. Instr., Suppl. 1, Vacuum Physics, 1951, p. 20–8.

[4] T.Wasserrab: Vakuumtechnische Fortschritte im Stromrichterbau. BBC-Nachr. 1951, Vol. 33, No. 4, p. 127–37.

[5] M. Benedict and C. Williams: Engineering Developments in the Gaseous Diffusion Process. McGraw-Hill, New York. Articles by A.O. Nier, C.N. Stevens and others: Mass Spectrometer for Leak Detection, p. 31–44, and R.B. Jacobs and H.F. Zuhr: New Developments in Vacuum Engineering, p. 45–70.

[6] W. Deck: Brown Boveri Rev. 1942, Vol. 29, No. 8, p. 202–4.

[7] M. Knudsen: Die Gesetze der Molekularströmung und der inneren Reibungsströmung der Gase durch Röhren. Ann. Phys. 1909, Vol. 28, p. 75–130.

[8] G.P. Brown, A. DiNardo, G.K. Cheng and T.K. Sherwood: The Flow of Gases in Pipes at Low Pressures. J. appl. Phys. 1946, Vol. 17, No. 10, p. 810–13.

MUTATOR-FED VARIABLE-SPEED DRIVES

621.34:621.314.65

The excellent regulation properties, high efficiency and small space requirements of the grid-controlled mutator, make it ideal for feeding variable-speed drives in heavy industry. By the adoption of "inertia-free" devices, it has now become possible to overcome extremely difficult regulation problems. The present article describes, as typical example, a large rolling mill fed entirely by mutators.

In recent years voltage-regulated mutators have been finding increasing use for feeding variable-speed d.c. drives in heavy industry. With modern methods, utilizing the inertia-free voltage regulation characteristic of the mutator, problems of regulation can now be overcome which with the classical Ward-Leonard control system would be either impossible or at least difficult to solve. Particularly in the varied field of heavy-duty drives, the additional advantages of the controlled mutator—high efficiency, low initial outlay and maintenance costs, and the capacity to withstand considerable temporary overloads—have enabled it to compete successfully against the Ward-Leonard converter.

It is now intended briefly to consider the stage of development reached by mutator regulation, and the various fields to which voltage-regulated mutators can be applied.

Mutator-Voltage Regulation

Firstly, the principle of voltage regulation as applied to the mutator will be explained. The d.c. voltage output of an uncontrolled mutator bears a definite relation to the phase voltage of the transformer feeding the mutator, whereas in a grid-controlled mutator the d.c. voltage can be varied continuously from its full value down to zero.

When the control grid carries a negative bias with respect to the cathode, the anodes remain blocked and cannot fire, even when the anode voltage is positive. Positive voltage impulses superimposed on the negative grid bias govern the firing of the anodes. Once the arc has struck, however, it cannot be quenched by grid control, even with a negative grid potential. The anode fires until the next positive anode fires or the anode voltage itself becomes negative. Fig. 1 shows the d.c. voltage U_0 of a firing six-anode mutator for various phase positions α_0 to α_7 of the positive grid control impulse against the anode voltage U of the mutator transformer. The mean value of the d.c. output voltage is given by the shaded portion of the voltage-time area. At α_0 the anode fires when the vector sum of its own voltage and that of the anode about to cease firing becomes zero, while the d.c. voltage attains its maximum value, equal to that of an uncontrolled mutator. As α is increased, the firing of the anodes is delayed, the resultant d.c. voltage diminishes and at α_7 has almost disappeared. In this way the voltage can be regulated down to zero.

The voltage conditions as shown in Fig. 1 only apply when the mutator carries a pure resistive load. Should the load produce a back e.m.f., such as in a d.c. machine, and

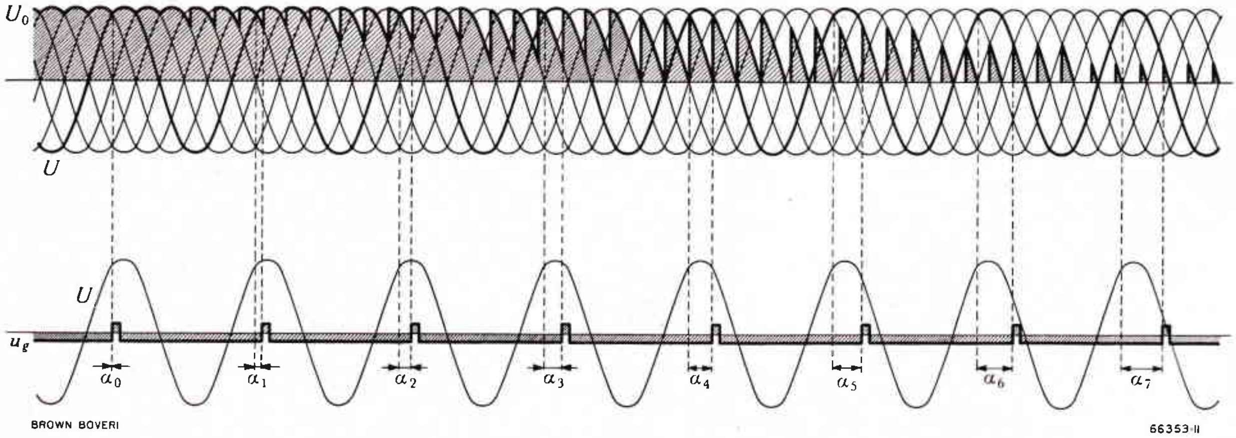


Fig. 1. — Voltage regulation in a six-anode mutator

U_0 = D.C. voltage when firing U = Phase voltage of one anode u_g = Grid voltage of anode at voltage U
α_0 = Natural firing point (max. d.c. voltage) α_1—α_7 = Firing points with increasing regulation (i.e. decreasing d.c. voltage)

By increasing the angle α, the d.c. voltage can be steadily reduced from its maximum value to zero.

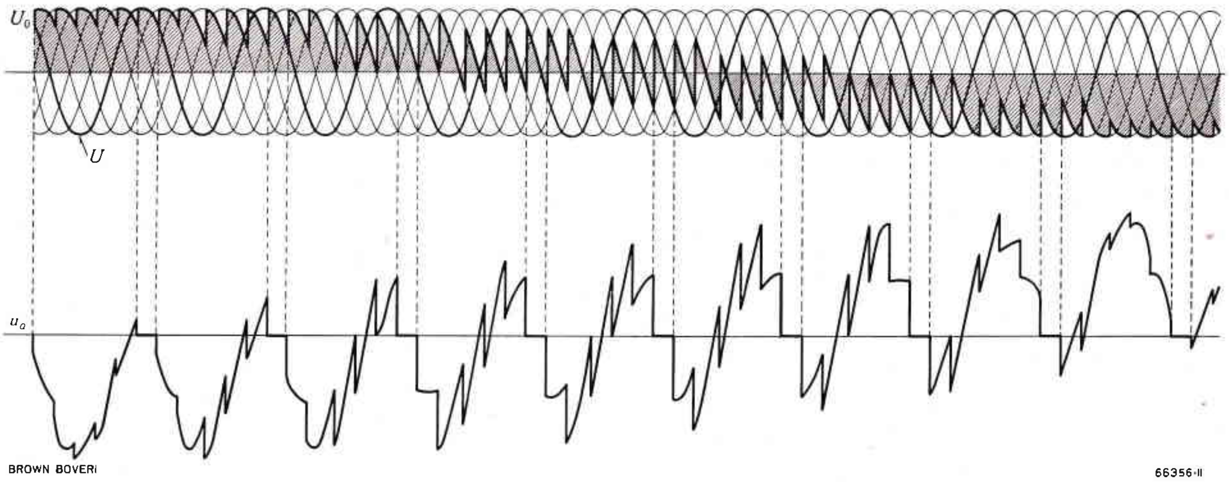


Fig. 2. — Voltage relationships in a six-anode mutator under various operating conditions

U_0 = D.C. voltage when firing U = Phase voltage of one anode u_a = Voltage between anode and cathode for the anode at voltage U

Left: Rectification Centre: No-volt operation Right: Inversion

steps are taken to maintain the current under all operating conditions, then as can be seen from Fig. 2, further retardation of firing causes the mutator voltage to reverse, i.e. although the direction of the current remains the same, the direction of energy flow varies alternately. Thus the mutator feeds back energy into the a.c. supply, by converting the d.c. of the machine into a.c.

The following working conditions are therefore possible:

(a) A.C.-D.C. operation (rectification), the mutator converting a.c. into d.c.

(b) No-volt operation, the d.c. voltage of the mutator being reduced to zero.

(c) D.C.-A.C. operation (inversion) the mutator accepts d.c. and converts it into a.c.

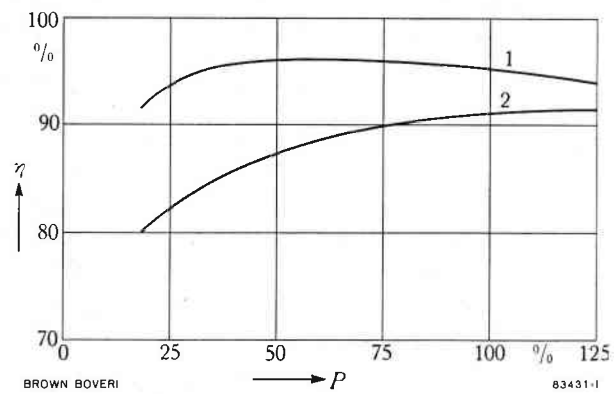


Fig. 3. — Comparison of efficiencies of a mutator set and a Ward-Leonard converter, as a function of the load P, both rated at 3000 kW and 1000 V

1 = Efficiency of mutator set
2 = Efficiency of Ward-Leonard converter

Fig. 2 shows that the circuit duty of the mutator under these operating conditions varies considerably. Whereas during rectification the anode blocking voltage is mainly negative, during inversion positive values become preponderant.

It is thus clear that the mutator is well suited not only to feeding variable voltage to d.c. motors, but also to braking motors and converting the brake energy surrendered by the motors back into a.c. For this purpose it is only necessary to ensure that the d.c. current maintains the same direction in the mutator for all operating conditions. Compared with the Ward-Leonard system, the mutator possesses the following advantages:

(a) Speed of Regulation

As the mutator is a static piece of apparatus and its excitation field has no time constant, d.c. voltage regulation is practically instantaneous. This is particularly favourable in certain applications where it is important, for example, to maintain the speed of the motor constant while the load is subject to sudden surges.

(b) Efficiency

The efficiency of a mutator is more or less constant over a considerable load range, due to the lack of rotating parts. Fig. 3 draws a comparison between the efficiency of a mutator and that of a 3000-kW, 1000-V, Ward-Leonard set. Even on partial loads the high efficiency of the mutator renders it superior to the converter, particularly when the

main consideration is relatively short load surges, separated by intervals of no load (drive of ingot rolling mills and conveyor systems).

(c) Space Requirements and Erection

Expensive and heavy foundations are unnecessary for the erection of mutators. Less space is occupied than by a Ward-Leonard set of equivalent rating. Building costs are thus reduced considerably.

Compared with Ward-Leonard or Ilgner converters the mutator has the following disadvantages:

(a) Load surges are transferred direct to the a.c. supply system. Cases involving high powers with heavy load surges should therefore be studied individually to decide whether the supply system can withstand the resultant current surges.

(b) During the transition from motoring to braking (regeneration) using the economical single-anode system, the polarity of either the armature circuit or field winding must be reversed. The reversal of the armature is performed at zero current by means of a reversing switch, while the field winding is reversed by two auxiliary mutators connected anti-parallel. A direct change-over from motoring to braking is only possible with the anti-parallel arrangement (double-anode circuit).

(c) Voltage regulation by means of grid control reduces the power factor of the mutator and gives rise to a greater amount of harmonic ripple than when the d.c. voltage is regulated. This drawback can, however, be overcome by using special circuits (phase sequence control), and for most applications is of only minor significance.

Status of Regulation Techniques using Mutators

As has already been shown, the mutator has the important advantage over all other converters that regulation is almost inertia-free. The only possible source of inertia is in the grid control gear and the frequency of the a.c. system.

Fig. 4 shows the effect on the voltage of a sudden jump in the control impulse from α_1 to α_2. The anode still firing from α_1 continues until the following anode fires at α_2; thus within one half-cycle the mutator can change from rectification to inversion, that is to say the minimum time to effect a 200% voltage variation at 50 c/s is only about 0·01 s.

Depending on the conditions imposed on a variable-speed drive the design of the regulating system will differ for the various applications. Brown Boveri can supply any of the following four regulating systems:

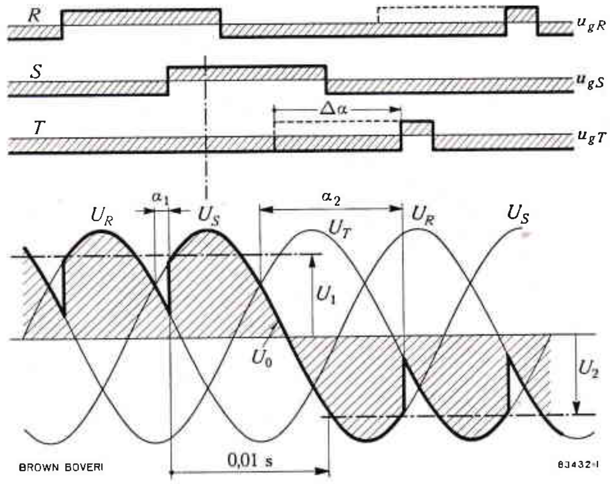


Fig. 4. — Variation of mutator d.c. voltage when the grid control impulse is suddenly delayed

U_0 = D.C. voltage when firing
U_R, U_S, U_T = Phase voltages of anodes R, S, T
u_{gR}, u_{gS}, u_{gT} = Grid voltages of anodes R, S, T
U_1, U_2 = Mean d.c. voltages
α_1 = Anode firing point before grid control impulse delayed
α_2 = Anode firing point after grid control impulse delayed
$\Delta\alpha$ = Angle of delay of grid control impulse

(a) Rolling-contact regulator in conjunction with magnetic grid control sets.

(b) Pure magnetic regulator in conjunction with magnetic grid control sets.

(c) Electronic regulator in conjunction with high-speed magnetic grid control sets.

(d) Electronic regulators in conjunction with thyratron controls.

The circuit diagram of a mutator-controlled variable-speed motor is illustrated in Fig. 5. Sinusoidal voltages are fed to the grid control set 8 through a rotary regulator 6 and grid-control transformer 7. In (a) and (b) above, the grid control set consists basically of premagnetized chokes which, depending on their degree of magnetization, cut out definite portions of the voltage-time area of the a.c. input voltage. Thus the anode firing point is variable over a certain range. Regulation is achieved by means of regulators 13 and 14 which vary the premagnetization current fed to the control set. Such a method distinguishes itself by the simple and clear layout of all components; the regulating accuracy attainable depends on the precision of the regulators employed. Using astatic rolling-contact regulators an accuracy of 0·5 to 1% can be attained, which suffices in many cases. For such applications Brown Boveri make a special rolling-contact regulator with a high rate of response. It possesses the added advantage of being easily adaptable to a variety of regulation duties.

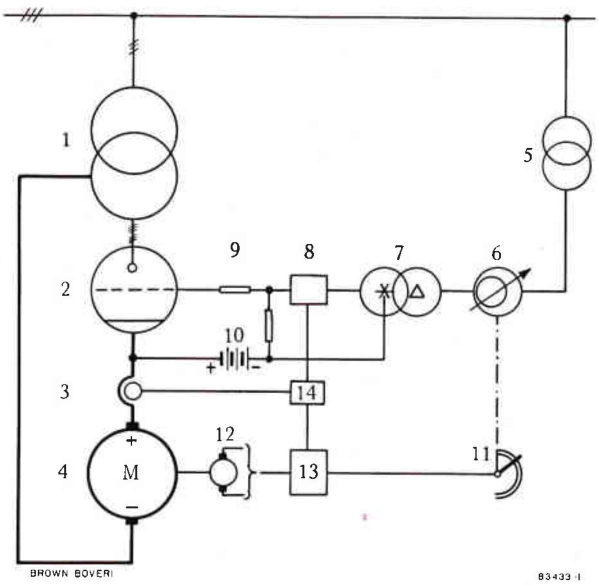


Fig. 5. — Circuit diagram of a mutator-controlled motor with speed regulation and maximum current limitation

1 = Mutator transformer
2 = Mutator
3 = D.C. transformer
4 = Motor
5 = Auxiliary transformer
6 = Rotary regulator
7 = Grid control transformer
8 = Grid control set
9 = Grid resistors
10 = Negative grid bias
11 = Speed selector
12 = Tachometer dynamo
13 = Speed regulator
14 = Current-limiting regulator

For many applications, for example to limit the current, it is frequently advantageous to employ a pure magnetic regulator consisting of premagnetized cores having a sharp bend in their saturation curve, which are mounted on the cathode busbar. The d.c. current flowing in this bar acts against the premagnetization ampere-turns, so that at a certain d.c. current the cores are desaturated and from this point onwards affect the grid control set in such a manner that the controlling impulses for the mutator are delayed.

Fig. 6a illustrates the manner in which a simple current limiting regulator of this type operates when the driving motor of a rolling mill stand is started up. The wheel on the control stand is turned from zero to the maximum d.c. voltage position within 0·4 s. At first the current increases very rapidly and is held by the magnetic regulator at the maximum starting value of 3500 A. With this current the motor is accelerated up to its rated running speed. Fig. 6b shows the same processes when the motor is retarded.

The previously mentioned methods of regulation are not entirely inertia-free. Not only have they a definite inherent delay (due to the rolling-contact regulator), but the inductances in the magnetic regulators and control

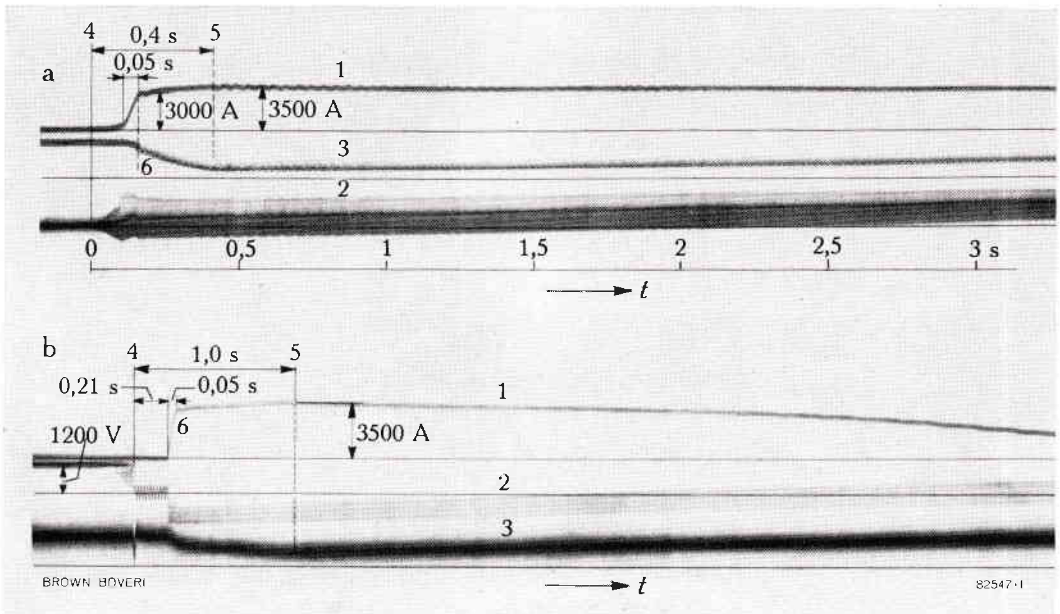


Fig. 6. — Starting and braking of a rolling mill motor with magnetic current limitation

(a) Starting (b) Braking down to zero revolutions

1 = D.C. current (cathode current of mutator)
2 = D.C. voltage of mutator
3 = Control current
4 = Start of firing point delay, regulated from control stand
5 = Control stand in end position for maximum d.c. voltage (Fig. 6a) or position of rest (Fig. 6b)
6 = Current-limiting regulator cuts in

The magnetic current-limiting regulator ensures that the motor receives constant current when accelerating or decelerating.

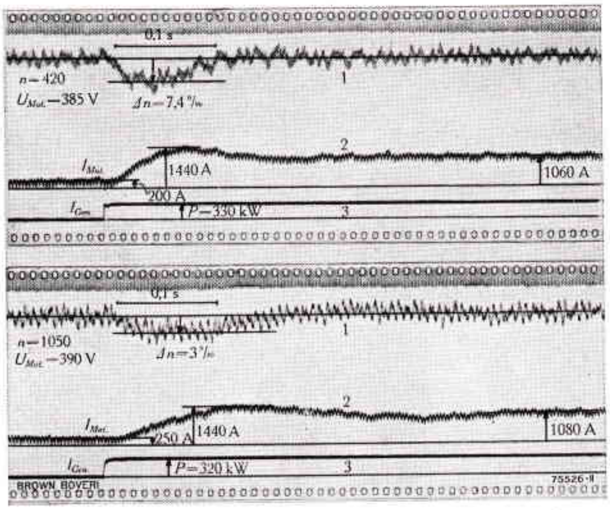


Fig. 7. — Speed reduction due to load surge on mill motor with electronically controlled mutator

Top: no-load motor speed at full field strength Bottom: maximum working speed at reduced field strength

n = Speed (rev/min) 1 = Tachometer voltage 2 = Motor current 3 = Power surge

Note the small drop in speed and the short time in which the temporary speed variation is corrected.

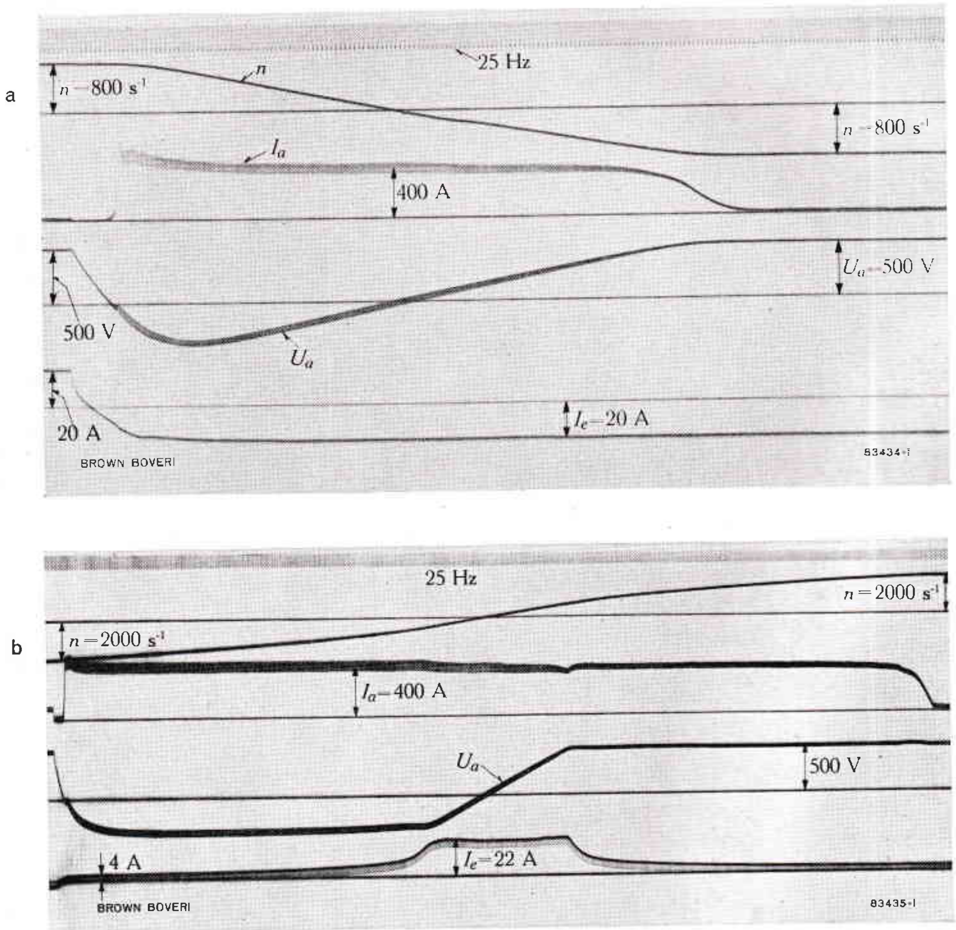


Fig. 8. — Control of reversal: a without reducing field strength, b with field strength reduced by 1:3

n = Motor speed (rev/min) I_a = Armature current U_a = Armature voltage I_e = Excitation current

On receipt of an impulse to reverse the field, the mutator regulating the armature current is blocked. As soon as reversal is complete it is switched over to inversion. During the change-over the armature current is held constant by the current-limiting regulator.

sets reduce the rate of response still further, which is undesirable in certain applications. A means of grid control which responds very rapidly can be obtained by using an electronic regulator [1].[1] In such a control the grid control set 8 in Fig. 5 is made up of thyratron tubes which regulate the grid voltage by electronic means. The rate of response attainable with a thyratron control of this nature is equal to the highest possible regulation speed of the mutator itself, i.e. it is dependent solely on the supply frequency (Fig. 4). The range of adjustment of such a control is approximately 120 electrical degrees, i.e. the mutator d.c. voltage can be varied from zero to the maximum possible value without adjustment of a rotary regulator.

The oscillogram in Fig. 7 demonstrates the rapidity with which such a control operates. It was recorded on a wire-rolling mill connected on the unit control system (each mill motor fed by its own grid-controlled mutator), where the conditions laid down regarding maintenance of the set speed on the various stands were particularly exacting. A load surge up to the rated torque of the motors causes a temporary decrease of only 0·3 to 0·74 per cent of the rated speed. This decrease is corrected in 0·1 s. The motors rely solely on natural flywheel effect and need no assistance from additional inertia sources.

A new magnetic rapid grid control set has recently been developed by Brown Boveri, the response of which is practically on a par with that of the electronic control [2, 4]. This set possesses important advantages compared with the electronic method in that its range of regulation is wider, covering 160 electrical degrees, and it requires no tubes to produce the grid control impulses. With a range of 160 electrical degrees, the mutator can be switched over from rectification to inversion in 13 ms. An additional rotary regulator therefore becomes superfluous. This form of control is well suited to single-anode reversing drives, e.g. for reversing rolling mills. An inertia-free electronic regulator can be employed to advantage. Using a control set of this kind nearly all the problems of mutator regulation can be solved and overcome. Fig. 8 illustrates the reversal of a motor which receives its energy from a mutator with a rapid grid control set. Two small pumpless mutators connected anti-parallel feed the field winding of the motor. The two mutators also have rapid grid control. This arrangement enables the reversing switch to be dispensed with.

On receipt of the impulse to reverse the field, the mutator regulating the armature current is blocked and switched over to inversion; the no-load current of the motor disappears. As soon as the field is completely reversed the armature mutator is released. Braking is carried out first by strengthening the motor field and then steadily reducing the mutator voltage. The oscillogram in Fig. 8 b depicts the smooth manner in which current limitation is accomplished.

[1] The figures in brackets refer to the bibliography at the end of the article.

Application of Regulated Mutators Feeding Heavy-Duty Drives

In practice the voltage-regulated mutator has found ready acceptance for supplying variable-speed drives [3]. It particularly excels in connection with high-power drives and in cases where the demands on the speed of regulation of the drive are exacting. As an example of mutators applied to a rolling-mill drive, the Issoire Works in France will now be described. This installation was supplied by the Cie Electro-Mécanique, Paris, and Brown Boveri, Baden in cooperation and was taken into service in 1949. In this aluminium rolling mill all the mill motors and the majority of the auxiliaries are fed by mutators.

The mill comprises the following sections:

Reversing mill
Three-stand hot rolling mill
Two-stand cold rolling mill and reeler.

The electrical layout of these three sections is shown in Fig. 9.

Reversing Mill

The reversing mill (Fig. 10) is driven by motor 7, which has a continuous rating of 7000 h.p., a maximum emergency capacity of 21 000 h.p., and a cut-out torque of 300 mt at 50 rev/min. This motor receives its energy from three eighteen-anode water-cooled mutators 2 connected in parallel via reversing switch 3 and change-over switch 4. The mutators are controlled from control stand 8. The desired speed set on the stand (speed selector 10), is compared with the actual speed of the motor (tachometer dynamo 7a) by means of the magnetic speed regulator 9; the grid control 5 of the mutators is influenced through the medium of the magnetic current-limiting regulator 6 in such a manner, that the speed of the reversing motor remains practically unchanged from no-load to full-load.

On reversal of the motor, at zero current, the reversing switch 3 is automatically operated from the control stand and the mutators are simultaneously switched over to inversion. Until it comes to rest the motor feeds back energy into the a.c. supply system via the mutators.

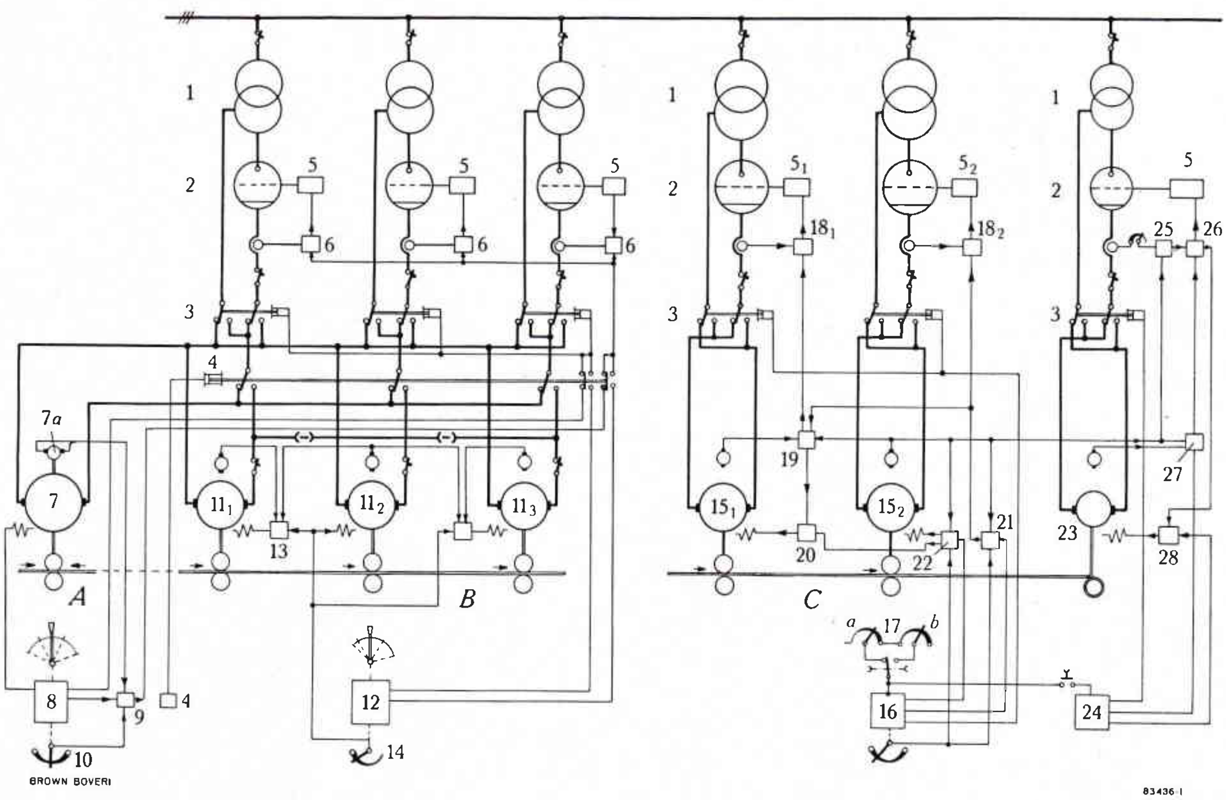


Fig. 9. — Electrical layout of a mutator-fed aluminium rolling mill

A = Reversing mill *B* = Three-stand hot rolling mill *C* = Two-stand cold rolling mill and reeler

1 = Mutator transformer
2 = Mutator
3 = Reversing switch
4 = Change-over switch from section *A* to section *B*
5 = Grid control set
6 = Magnetic current-limiting regulator
7 = Reversing motor 7000/21 000 h.p.
7a = Tachometer dynamo
8 = Control stand of section *A*
9 = Magnetic speed regulator
10 = Speed selector
11_1, 11_2 = 4000-h.p. motors of section *B*
11_3 = 2500-h.p. motor of section *B*
12 = Speed regulator
13 = Speed regulator
14 = Field regulator
15_1, 15_2 = 2500-h.p. motors of section *C*
16 = Controls for section *C*
17 = Speed selector *a* feed-in *b* rolling
18_1, 18_2 = Current-limiting regulator
19 = Mutator coordination regulator
20 = Coordination regulator for excitation of motor 15_1
21 = Speed regulator varying mutator voltage
22 = Speed regulator varying motor excitation
23 = 1000-h.p. reeler motor
24 = Controls for reeler mutator
25 = Acceleration regulator
26 = Tension regulator
27 = Reeler speed coordinator
28 = Reeler field regulator

Three-Stand Hot Rolling Mill

The three stands are driven by three motors, two of which are rated at 4000 h.p. and the other at 2500 h.p. The roller conveyor of the reversing mill continues as far as the hot rolling mill. The continuous sheet which has passed through the reversing section proceeds to the hot rolling section without renewed heating. On completion of the rolling process in the reversing mill the mutators are changed over, at zero current, by switch 4, to the busbars of the three hot-mill motors. Simultaneously, the polarity of the grid control is reversed on the control stand 12. While the material is passing on the roller conveyor from one section to the other, the three hot-mill motors are running up. The current is limited by the magnetic current-limiting regulator 6, so that the motors accelerate with their maximum permissible current (see oscillogram Fig. 6 a). In the course of the rolling process the speeds of motors 11_1 and 11_3 maintain the correct relation to that of 11_2 due to the action of speed regulator 13. This regulates the field of the two outer motors, the busbar voltage remaining constant.

After the material has traversed the hot mill the motors are brought to rest by switching the mutators over to regeneration (oscillogram Fig. 6b) and then switching them back on to the reversing mill. This arrangement allows the best possible utilization of the mutators.

Two-Stand Cold Rolling Mill with Reeler

This section of the mill imposes particularly exacting demands on the regulating system. The final rolling of the sheets must be carried out with a definite and accu-

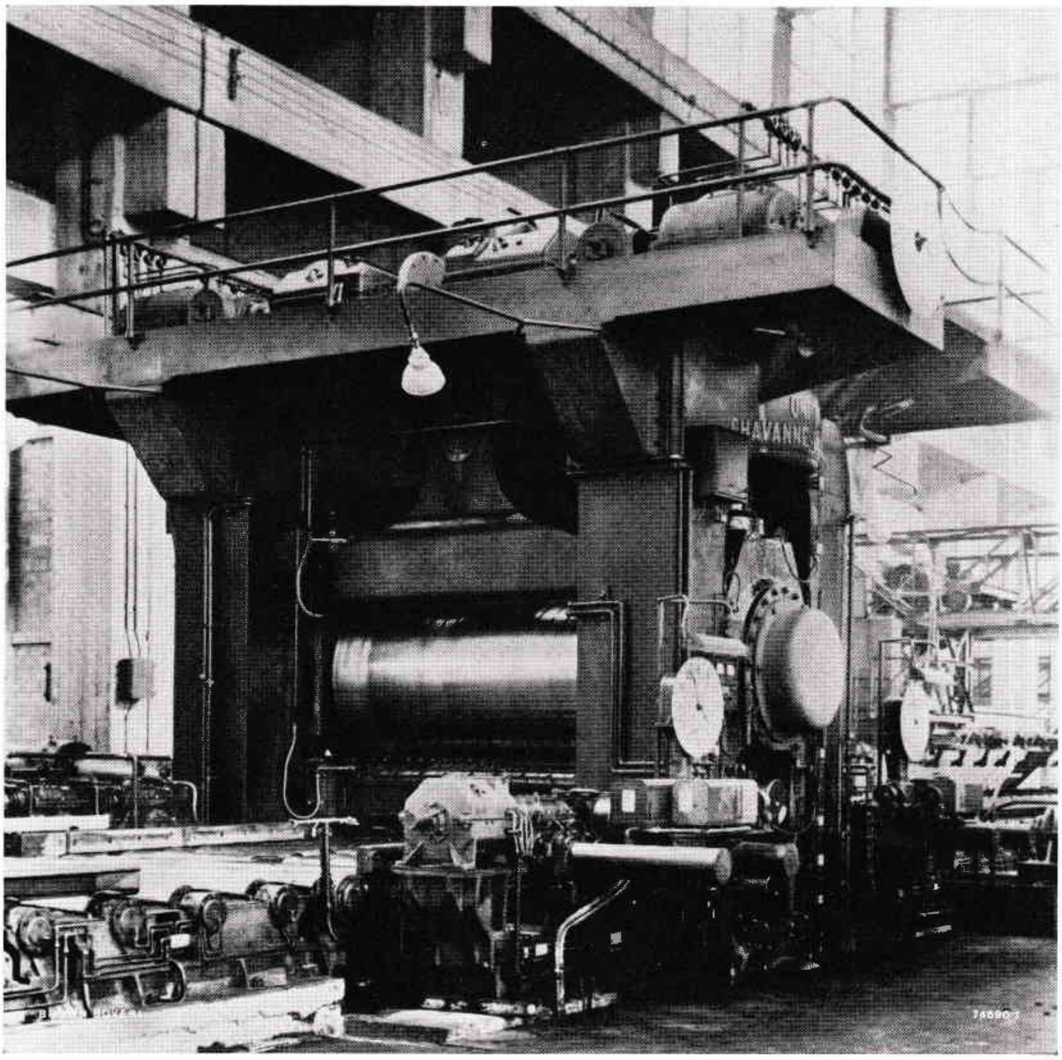


Fig. 10. — Mutator-fed reversing mill

The reversing motor has a continuous rating of 7000 h.p., a maximum emergency capacity of 21000 h.p. and a cut-out torque of 300 mt at 50 rev/min.

rately maintained tension between the first and second stands and reeler, respectively. For feeding-in the sheet motors 15_1 and 15_2 are run at a low speed. As soon as the sheet reaches the reeler all three motors are run up to full speed. During acceleration the set tension must also be accurately maintained. Just before the end of the sheet enters the section the motors are slowed down to the feed-in speed by switching the mutators over to regeneration, and as the final part emerges from stand 2, the reeler is stopped.

To enable these operations to be properly carried out each of the three motors is connected to its own mutator. The two mill motors each have a twelve-anode water-cooled mutator and the reeler a six-anode air-cooled model. Fig. 11 shows one of the two 2500-h.p. motors 15 incorporating a tachometer dynamo. The whole rolling mill is push-button controlled, the desired rolling speeds being pre-set by the selecting device 17. The grid control of the two mutators feeding the mill stand and the excitation of the two 2500-h.p. motors 15 is effected by control set 16. The mutator feeding the reeler motor is regulated by control 24. The grid impulses from control 16 proceed through speed regulator 21 and current-limiting regulator 18_2 to the grid control set 5_2 of the mutator for the second stand, and through coordinating regulator 19, current limiting regulator 18_1 to grid control set 5_1 of the mutator for the first stand. The coordinating regulator 19 maintains the relation between the speeds of motor 15_1 and motor 15_2 in such a way that a constant tension is exerted between the two stands. Not only does it vary the d.c.voltage of the mutator 2_1 but also, through field regulator 20, the excitation of motor 15_1.

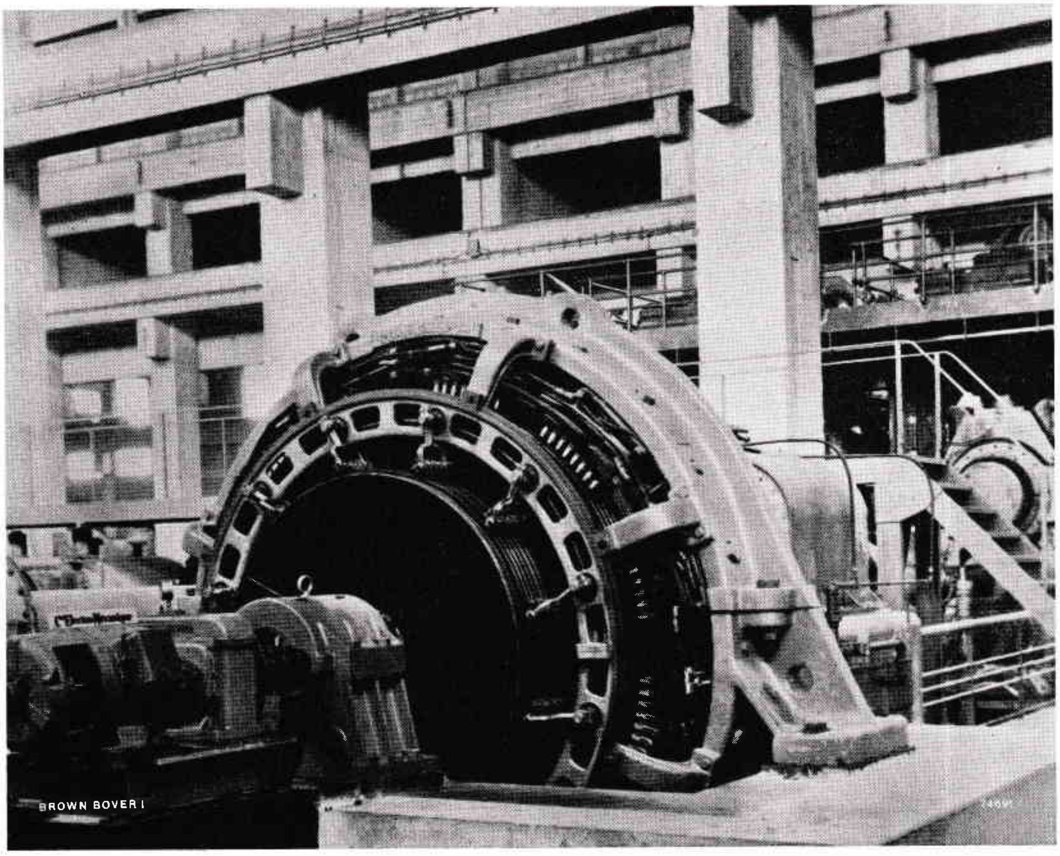


Fig. 11. — Mill motor rated 2500 h.p. at 1200 V and 350 rev/min connected on unit-control principle, incorporating tachometer dynamo and used to drive the two-stand cold rolling mill

Regulation of the reeler mutator is performed on the one hand by regulator 27 in relation to the speed of motor 15_2 and on the other by tension regulator 26, which acts as current regulator and maintains a constant tension in the material. While the motors run up from feed-in to full speed the acceleration governor 25 ensures that the reeler runs up at the same speed as motor 15_2, and at the same time accurately maintains the set tension.

For the cold rolling section the proved Brown Boveri rolling-sector regulators were used exclusively. By appropriate modification of these regulators it was possible to solve the manifold regulation problems without having to resort to complicated rotary amplifiers or electronic apparatus. Feeding the continuous band of metal on to the reeler, using straps or clamps, demands accurate regulation, which is obtained with the equipment described.

Thus in this rolling mill three typical mutator circuit arrangements for feeding mill motors are brought together. These are:

(a) Reversing drive using a single-anode circuit, with speed regulation and maximum current limitation.

(b) Connection of various mutators and motors through busbars and regulation of individual motor speeds by varying the excitation of separate motors.

(c) Connection on the unit-control system and regulating the speed of individual motors, mainly by varying the mutator d.c. voltage by means of grid control.

The Issoire Works in France is only one of many such installations which could be mentioned. In recent years Brown Boveri have supplied similar drives to mills in Austria, Germany, Holland, Italy and Switzerland with, in some cases, even larger numbers of mutators. Some of these installations have already been described in earlier publications [1, 3]. A number of similar works are at present building, while others are already in production. It is hoped to make them the subject of a future article.

In the reversing mill described, off-load reversing switches are used throughout to switch the mutators over to braking duty; before effecting this operation they also change the polarity of the leads between motor and mutator. An alternative method of switching over to braking is to reverse the motor field instead of the ar-

mature leads. This method, simple as it is, previously failed owing to the exacting requirements of armature regulation. As a result of the recently developed grid control sets this method now becomes a very neat and practical proposition [4]. The motor field winding is fed by two small mutators connected anti-parallel and equipped with rapid grid control sets. With specially designed motors the field can be reversed so rapidly, without mechanical switches, that almost the same reversal time is attainable as when using a reversing switch.

This circuit has the great advantage that no mechanical switches whatsoever have to be operated, which thus increases reliability and simplifies maintenance. This improved circuit is specially suited to installations where reversing is frequent and maximum reliability essential, as, for example, with reversing mills and reeler drives. Such systems are now being manufactured by Brown Boveri.

MS 794 (KME) *H. Blatter*

Bibliography

[1] G. Wetten: Inertia-free Control of Continuous Rolling Mill Drives. Brown Boveri Rev. 1952, Vol. 39, No. 4, p. 114–18.

[2] G. Lemcke: Elektronische und magnetische Regelverfahren in kontinuierlichen und Umkehr-Warmwalzwerken. Stahl u. Eisen, 1953, Vol. 73, No. 18, p. 1156–61.

[3] H. Schirmer: Stromrichtergesteuerte Antriebe im Gebiet höherer Leistungen. BBC-Nachr. 1952, Vol. 34, No. 2, p. 62–71.

[4] W. Besthorn: Der Rapid-Gittersteuersatz, eine entscheidende Verbesserung im Regelkreis. E.H. Ludwig: Die jüngste Entwicklung der Umkehrsteuerungen bis zur Feldreversierung. BBC-Nachr. 1954, Vol. 36, No. 3, p. 88–97.

MUTATOR LOCOMOTIVES FOR 50-C/S SINGLE-PHASE A.C. SUPPLIES

621.335.2:621.314.65

Although none of the three types of locomotive for use on 50-c/s supply systems—with mutators, series-wound commutator motors or rotary converter sets—has been able to oust the others by sheer superiority, the mutator locomotive has definite advantages. Above all it offers the most economic opportunity of feeding d.c. motors from a 50-c/s supply line. The present article discusses this system and describes locomotives equipped in this way by Brown Boveri.

Designs of 50-c/s Locomotives and their Development Prospects

FROM the viewpoint of economy in stationary railway installations, drawing single-phase current from the national 50-c/s electricity system for traction purposes assumes considerable significance. Previous experience and the present stage of engineering development prove that 50-c/s locomotives can be built which are suitable and reliable for all conditions likely to be encountered in railway practice. Which design of locomotive—whether with mutators, 50-c/s series-wound commutator motors or rotary converter sets—is eventually chosen as the basic solution to the problem of utilizing the national electricity supply for *all* traction purposes, can only be decided from comprehensive operational experience and technical progress. A critical consideration of all the important comparison factors leads to the conclusion that so far none of the three locomotive systems mentioned, viewed as a means of traction, exhibits such advantages and disadvantages, as to warrant a unilateral trend in development. For the present, therefore, all three systems are used and will be further developed. This article, however, is only concerned with one of these, the mutator locomotive.

The Mutator Locomotive

The demand for maximum efficiency in the energy transmission between the high-voltage contact-wire and the 600/800-V d.c. traction motors is best fulfilled by the mutator locomotive; its application leads to favourable values for installed power, initial costs and distance between substations, also to the most economical spread of the annual energy consumption.

Of supreme significance to the economy of a 50-c/s railway supply system are the efficiency and power factor of the locomotive equipment. The mutator locomotive has a decidely higher *efficiency* than locomotives with commutator motors or rotary converter sets and therefore has a correspondingly favourable influence on the power economy of 50-c/s traction. Admittedly the power factor is best in converter locomotives with synchronous motors, but then these are the least efficient.

The values for the electrical energy at the current collector, on the low-voltage side of substations, and finally at the outgoing terminals of the power station are obtained simply by substituting the respective efficiencies of locomotive, contact-wire, substations and feeder.

The mutator locomotive combines the advantages of the single-phase locomotive—economic regulation of tractive effort and speed, greater distances between substations due to the high contact-wire voltage—with those of the reliable, robust and simple d.c. series-wound motor which has proved its supremacy under operational conditions. For working voltages between 600 and 800 V, the d.c. traction motor has given proof of its excellence during many years' service in

diesel-electric locomotives, tramcars and underground railways; it has also demonstrated that it is capable of frequent starts under the most difficult conditions in the low-speed range without its life being adversely affected. For the above voltage range the d.c. series-wound type is the lightest and cheapest of all commutator traction motors and requires the least maintenance.

As indicated earlier the various types of 50-c/s locomotives all possess inherent disadvantages which, for the time being, make it impossible for any one system to be described as superior to the others for all purposes. In the case of mutator locomotives these disadvantages are the need for additional elements compared with locomotives with 50-c/s motors, and the harmonic ripple in the contact wire and supply system caused by the mutators.

In the main these additional parts are the mutators with their cooling system, switchgear, controls and smoothing reactors. Furthermore, mutator operation demands a larger transformer. Nevertheless, these extra parts are relatively light and for the most part offset by the lower weight of the traction motors, so that there is little difference between the total weight of locomotives of equal power whether equipped with mutators or a.c. motors. Results so far appear to justify the hopes that modern air-cooled pumpless mutators will eventually become—in the same way as transformers or reactors—a static element which from the point of view of inspection and maintenance can be practically ignored. Then the disadvantage of the extra equipment, which assumes such importance in railway service, would as good as vanish.

In this article dedicated to the mutator locomotive it should also be mentioned that for motor-coaches the use of mutators is accompanied by an additional disadvantage in that a special compartment must be provided inside the coach to house the mutator tanks; this is usually not looked upon with favour by the railway companies, who prefer to utilize the whole of the coach interior for carrying passengers.

The ripple currents, already mentioned as a disadvantage of the mutator locomotive, are of odd-numbered orders and are introduced into the feeding system by single-phase mutator operation even when the a.c. voltage supplied to the mutator is exactly sinusoidal. The voltage drops caused by these ripple currents may produce voltage distortion at the points where feeders branch off to railway substations from the main supply system, which can impair the efficient working of the system and industrial plant connected to it. The degree of distortion depends primarily on the relation of the total load on the supply network to the traction load at the particular point. If this ratio is more than about 3:1, deviation from the sine-wave form will be less than 5 %, and thus remains well within the tolerable limits. If, however, it threatens to become less than 3:1, counter-measures must be taken. An acceptable solution can nearly always be found, either by shifting the feed-in points to favourably situated junctions in the supply system, by correct design of the transformers in respect of impedance voltage and by previous computation of the natural frequencies (to avoid any resonance phenomena from the outset). In such cases, comprehensive detailed planning will be worth while, as indeed it is for any project covering the supply of single-phase energy from the national supply system—here a network analyser can sometimes be of great assistance.

Special Conditions in Mutator Locomotives and their Effect on the Supply System

Efficiency

The efficiency of the mutator locomotive is the ratio of the power output at the wheel tread to the incoming power measured at the current collector. The incoming power is therefore the tractive power, i.e. the power measured at the wheel tread, plus the sum of all losses in the traction circuit and auxiliaries. In the mutator set these losses are made up of the following:

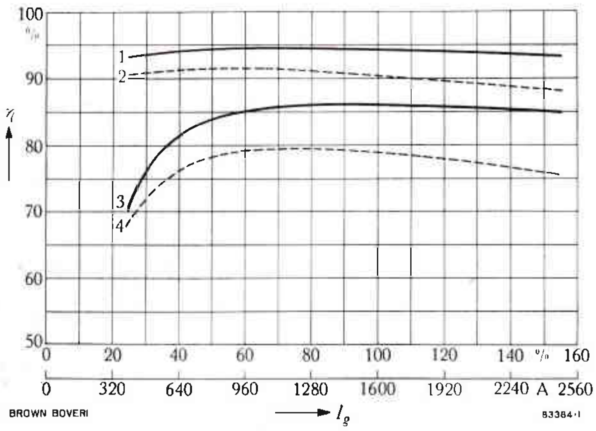


Fig. 1. — Calculated efficiency curves of Brown Boveri mutator locomotive as supplied to the Rhein-AG., Cologne, Germany

Curves 1 and 2 refer to the mutator set alone. Curves 3 and 4 to the complete locomotive on taps 28 (——— = motor voltage 960 V) and 10 (– – – = motor voltage 530 V) of the tapped transformer, as a function of the d.c. motor current I_g.

Arc losses

Winding and iron losses in the mutator- and regulating-transformers and in the anode reactors

Winding and iron losses in the smoothing reactor

Losses in the auxiliaries of the mutator set.

Calculated efficiency curves for the mutator set and mutator locomotive supplied by Brown Boveri to the Rhein-AG. (see p. 171) are given in Fig. 1. The high efficiency of the mutator installation remains constant for almost the entire load range from idling to overload, which is of considerable importance in view of the sudden variations in load experienced in railway service. The annual average efficiency of the mutator locomotive is probably in the region of 82 %, against about 76 % for locomotives with 50-c/s commutator motors and about 73 % for those with rotary converter.

Power Factor

Power factor is usually defined by the ratio

$$\frac{\text{Active power input}}{\text{Apparent power input}}$$

Whereas for currents and voltages with a sinusoidal wave-form the power factor is equal to $\cos\varphi$, in the mutator locomotive it is reduced on account of the reactive power produced by the ripple currents. In a mutator set, where the voltage has a non-sinusoidal wave-form, the total power factor is given by

$$\lambda = v \cos\varphi$$

(v = distortion factor, $\cos\varphi$ = displacement factor). The $\cos\varphi$ depends on the current and for a given mutator connection is governed by the inductances on the a.c side (anode reactors, stray inductance of transformers, inductance of the contact wire). The distortion factor v is primarily governed by the mutator connection; to a lesser degree it is also dependent on the inductances on the a.c. side and the current.

Reduction of the rectified voltage by grid control causes the power factor to deteriorate noticeably. For the greater part of the speed range, therefore, the voltage is not varied by grid control, but by a regulating transformer.

Fig. 2 illustrates calculated curves of the displacement factor $\cos\varphi$ and total power factor $\lambda = v \cos\varphi$ of the mutator locomotive for the Rhein-AG. at various tap settings of the regulating transformer. In practice power factors at the current collector of the following order are attainable:

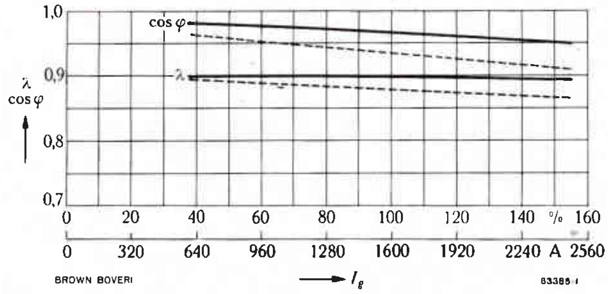


Fig. 2. — Power factor of the mutator locomotive supplied by Brown Boveri to the Rhein-AG.

Calculated curves of the displacement factor ($\cos\varphi$) and power factor $\lambda = v \cos\varphi$ (where v = distortion factor) on taps 28 (——— = motor voltage 960 V) and 10 (- - - = motor voltage 530 V) of the tapped transformer, as a function of the d.c. motor current I_g.

0·82 at 20 % running speed and continuous loading
0·86 at 60 % running speed and continuous loading
0·88 at 100 % running speed and continuous loading

The power factor at the current collector for the main part of the speed range is approx. 0·87, with an annual mean of about 0·8.

The Brown Boveri Mutator Locomotive E 244.11 of the Höllental Line

One of the first mutator locomotives ever built, the E 244.11,[1] was supplied in 1936 by Brown Boveri, Mannheim, to the German State Railways for the 20-kV, 50-c/s Höllental section; its one-hour rating is 2240 kW at 59·5 km/h (Fig. 3). This locomotive has given remarkable service and to date has completed well over a million kilometres, without any important modifications to its electrical equipment ever having proved necessary. In particular this long period has proved the applicability of the mutator to locomotive service, although this happens to be a ten-anode water-cooled mutator with vacuum pumps. Despite the heavy duty on the steep grades, the behaviour of the traction-motor commutators has been without reproach. Though this locomotive is

[1] See also A.E.Müller: Notice sur la locomotive d'essai à redresseur Brown Boveri E 244.11 de la ligne du Höllental. Document No. VIII, presented at the Journées d'information sur la traction électrique par courant monophasé de fréquence industrielle. Obtainable from Brown Boveri.

Further: H. Hutt: Die BBC-Gleichrichterlokomotive für die Höllentalbahn. BBC-Nachr. 1938, Vol. 25, No. 4, p. 123–34.

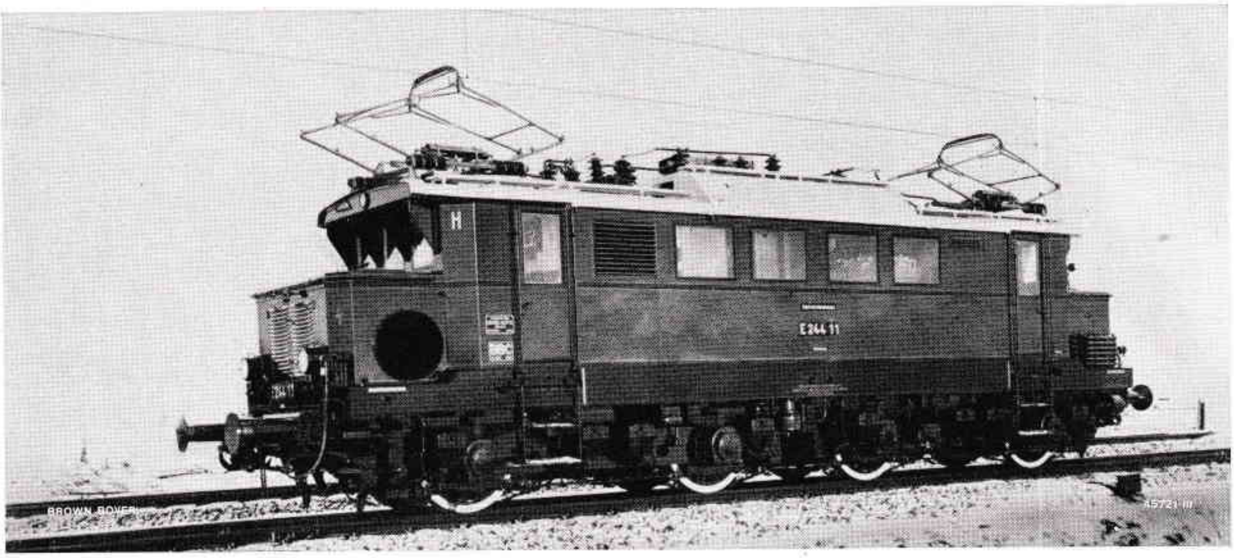


Fig. 3. — $B_0' B_0'$ locomotive No. E 244.11 (mutator locomotive) of the German Federal Railways, built by Brown Boveri in 1936 for the **Höllental line**

Designed for single-phase operation on 20 kV, 50 c/s, it has a one-hour rating of 2240 kW at 59·5 km/h. Electrical equipment supplied by Brown Boveri, Mannheim.

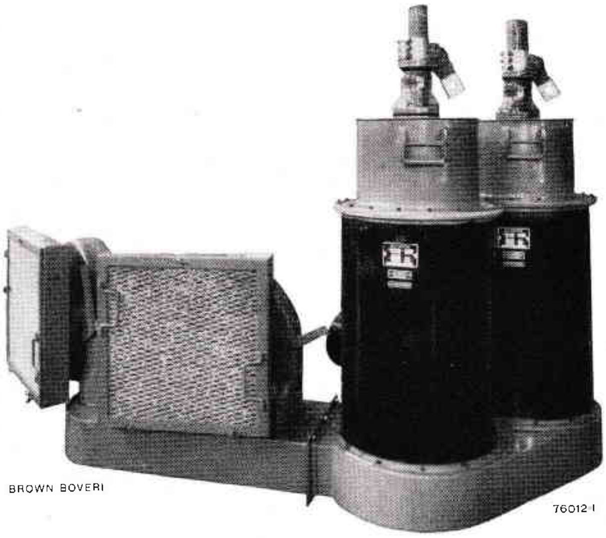


Fig. 4. — The two pumpless, air-cooled, single-anode mutators which, together with their fans and air-filters, were installed in 1951 for trials in the Höllental locomotive No. E 244.11

in the nature of a prototype, its running costs are no more than the average for the $16^2/_3$-c/s locomotives [1] operating in Southern Germany.

In 1951 Brown Boveri carried out the first trial with two single-anode mutators on the Höllental locomotive E 244.11 (Fig. 4), thus laying the foundation for the development of a reliable single-anode mutator for use in 50-c/s traction vehicles.

[1] O. Sexauer: Betrachtungen zur Frage der Unterhaltskosten elektrischer Lokomotiven für $16^2/_3$ or 50 Hz. Karlsruhe 1952.

The Brown Boveri Mutator Locomotive of the Rhein-AG., Cologne

Out of a total of fifty-six 50-c/s, 6000-V single-phase locomotives with rotary converter ordered by the Rhein-AG. (lignite mining and briquette-making company) from a number of German manufacturers in the autumn of 1952, seventeen were allotted to Brown Boveri, Mannheim. As a result of later discussions with the customer, it was agreed that one of the seventeen should be built as a mutator locomotive, while keeping as close as possible to the technical data and performance of the converter locomotives. Fig. 5 shows the general appearance of both types of locomotive, which have the following characteristics.

Axle arrangement	$B_0' B_0'$
Gauge	1435 mm
Axle load	30 t
Adhesion weight = weight in working order	120 t
Driving wheel diameter (new)	1120 mm
Total one-hour rating of traction motors at 760 V terminal voltage, and 680 rev/min.	1480 kW (2000 h.p.)
Corresponding tractive effort at wheel tread	21·6 t
Corresponding running speed	24·4 km/h
Max. starting tractive effort at wheel tread	38 t
Max. speed	70 km/h

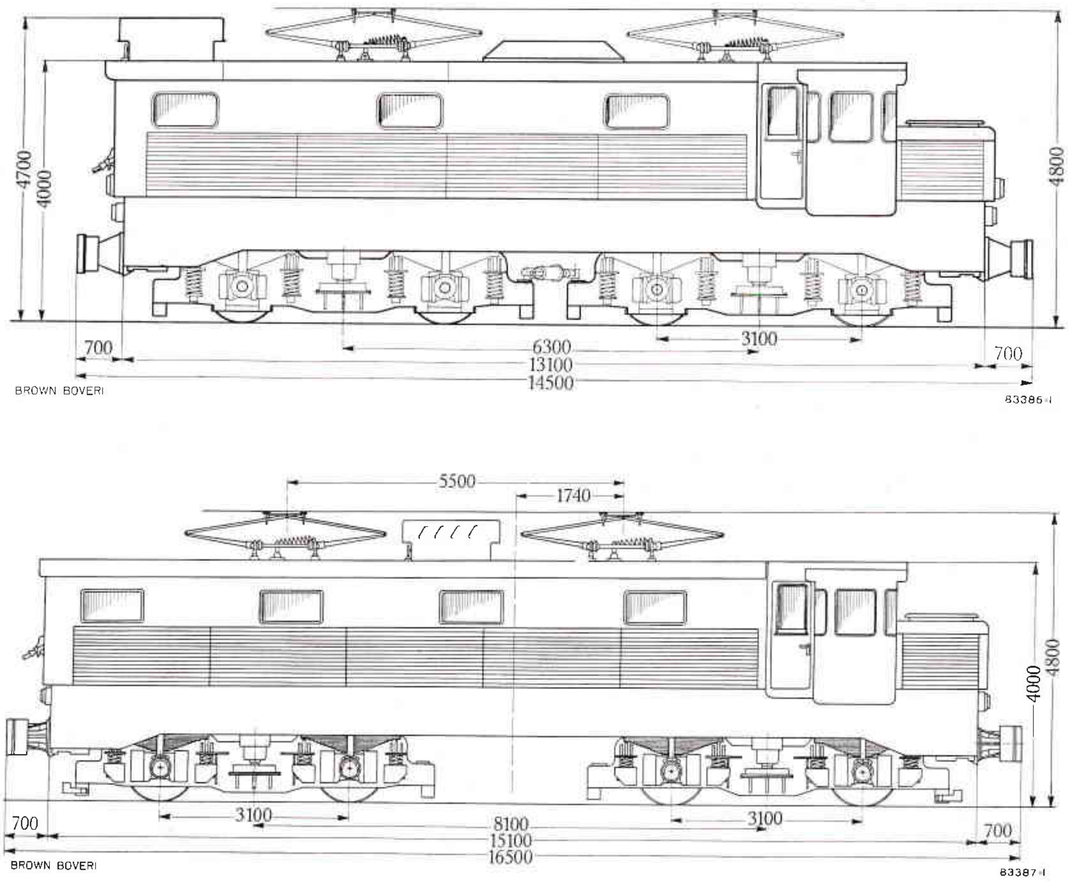


Fig. 5. — Exterior view of a $B_0'B_0'$ converter locomotive (above) and a $B_0'B_0'$ mutator locomotive (below) supplied by Brown Boveri to the Rhein-AG., Cologne, Germany

Mutator and air-blast circuit-breaker manufactured in Baden, all other electrical equipment in Mannheim. Performance figures for both types: standard-gauge locomotive for single-phase current at 6 kV, 50 c/s, with a one-hour rating of 1480 kW at 24·4 km/h. Max. speed 70 km/h. Total weight 120 t.

The mutator locomotive now being built for the Rhein-AG.—the mutators and air-blast circuit-breaker being supplied by Brown Boveri, Baden, the remainder of the electrical equipment by Brown Boveri, Mannheim—has to satisfy the typical and difficult conditions experienced in open-cast lignite mining. The three following functions have to be considered: slow haulage, motoring, braking. As the converter locomotives were supplied with regenerative braking, the customer specified the same facility for the mutator locomotive. This is feasible, but the electrical equipment and connection become more complicated than for rheostatic braking. The basic circuitry of the locomotive is shown in Fig. 6.

Slow Haulage

When the wagons which remove the excavated material are being loaded, the whole train moves under the belt of the conveyor at a speed of 0·5 m/s (i.e. 1·8 km/h). The capacity of a modern bucket-wheel excavator used for open-cast mining and tipping can be up to 2·4 m^3/s. A train of the Rhein-AG. consisting of seven filled wagons has a total weight of 1680 t. To ensure even loading at this high delivery rate, the locomotive is remote-controlled in both directions of travel from the excavator by means of v.h.f. radio.

For the mutator locomotive, the customer stipulated the same traction motors as for the converter locomotives which have a series field winding and separate exciter winding. For slow haulage, the tractive effort/speed regulation of the motor is undertaken by a "soft" grid control system; the motors run exclusively in shunt.

Motoring

For motoring the field windings and armatures of the motors are coupled in series, while all separate exciter windings are connected in series and fed from one exciter

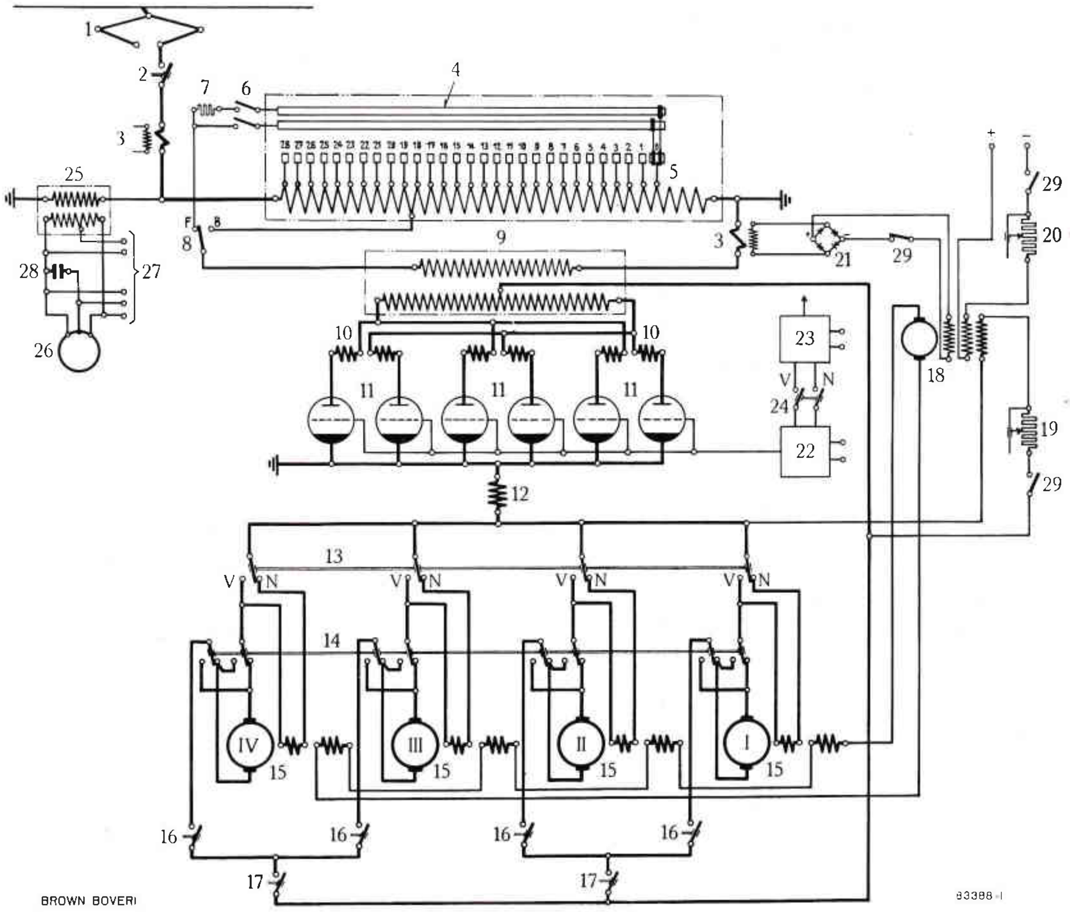


Fig. 6. — Simplified circuit diagram of the $B_0'B_0'$ mutator locomotive as supplied to the Rhein-AG.

1 = Current collector
2 = Circuit-breaker
3 = Current transformer
4 = Tap changer
5 = Regulating transformer
6 = Arc suppression switch
7 = Damping resistor
8 = Motoring and braking change-over switch
9 = Mutator transformer
10 = Anode reactor
11 = Single-anode mutator
12 = Smoothing reactor
13 = Change-over switch for slow haulage
14 = Reversing switch
15 = Traction motors
16 = Motor isolating contactors
17 = D.C. circuit-breaker
18 = Separate exciter
19 = Field regulating rheostat
20 = Braking rheostat
21 = Rectifier for field excitation proportional to current
22 = Grid control system
23 = V.h.f. receiver for slow haulage
24 = Grid control switch
25 = Auxiliary transformer
26 = Arno converter
27 = Auxiliary voltages
28 = Capacitor
29 = Cut-out

V = Slow haulage N = Normal running

proportionally to the armature current. The effort-speed control is performed by high-voltage tap-changing equipment (for the main speed range) in conjunction with the mutator grid control (for starting).

Regenerative Braking

During regenerative braking, the direction of current flow must be maintained, as the mutators can only pass current in the one direction. The direction of the power is varied by reversing the voltage. During the change-over from motoring to regenerative braking the mutators are switched over to maximum inversion. The excitation of the motors must be such that the resultant field causes the electromotive force to be reversed, whereby the field produced by the separate exciter windings must be preponderant and the motors function as compound generators. A control system based on the Contiflux process[1] ensures that these conditions are accurately maintained.

MS 790 (KME) *A.E. Müller*

[1] See BBC-Nachr. 1954, Vol. 36, No. 3.

THYRATRONS IN INDUSTRY

621.385.38

This article, describing the properties and operation of thyratrons, emphasizes the conditions essential for efficient working and explains the differences between tubes containing mercury vapour and those filled with an inert gas.

IN the article entitled "Mutator-Fed Variable-Speed Drives" on page 158 of this issue, reference is made to a grid control set (see Fig. 5) which, in cases requiring precision of regulation with extremely rapid response, consists appropriately of an electronic control set incorporating thyratrons. Anyone concerned with the use of mutators is almost certain to encounter their first cousins, the thyratrons, and it is therefore within the scope of this publication to describe certain aspects of the functions of this class of tubes. These are essentially controllable rectifier tubes with a heated cathode and gas filling; to enable their manner of operation to be more easily understood, the most important phenomena in uncontrolled rectifier tubes will first be examined.

Gas-Filled Hot-Cathode Rectifier Tubes

A gas-filled rectifier tube consists of a sealed glass bulb containing a heated cathode as the source of electrons, and at a fixed distance from it, an anode. At first sight, therefore, there is nothing to distinguish these tubes from the wide variety of vacuum rectifier tubes to be found in the rectifier section of the majority of radio receivers. The main difference, however, is in the gas filling, be it mercury vapour, hydrogen, an inert gas, or, in the future perhaps, caesium vapour. This filling (at a pressure of the order of 10^{-2} Torr) is ionized by the electrons emitted by the cathode when the anode is positive. Thus the stream of electrons flowing from cathode to anode (known as anode current) can become much greater than in the comparable vacuum tube at equal anode voltage and having the same physical dimensions. The reason for this is that the space-charge cloud, which occurs in every vacuum tube and opposes the passage of electrons, is continuously neutralized by the positive gas ions.

Naturally, this is conditional on the cathode possessing a capacity for giving off electrons, known as emissivity, in proportion to the desired anode current. Highly emissive cathodes are obtained when the cathode supports, in the form of a wire spiral or a wavy ribbon of metal strip or wire braid, are coated with a layer of one or more alkaline earth oxides. The cathode support usually conducts the heating current, under the direct influence of which it becomes hot (direct heating). Where the mean anode current is over 20 A it has been found preferable—in order to dispense with excessively thick heater conductors which besides the heating current also carry the heavy anode current—to use heater elements which are separate from the cathode supports (indirect heating.)

If a d.c. voltage becoming increasingly positive with respect to the cathode is applied to the anode of a gas-filled rectifier tube via an external resistor, a very small current (a few microamperes) will be recorded until a certain critical voltage (known as the firing voltage) is reached. When the firing voltage is exceeded, which for each gas filling will depend on the gas pressure and the distance between the electrodes, a sharp rise occurs in the anode current: the tube has fired. The voltage drop in the tube now falls to the arc voltage, which for example in mercury-vapour tubes operating under favourable conditions (to be referred to later in connection with Fig. 4) amounts to 15 V for practically all values of anode current. An arc once struck will extinguish when the anode voltage becomes less than the arc voltage.

If an alternating voltage is applied to the anode, the tube fires with each positive and extinguishes with each negative half-cycle, which accounts for its rectifying action. The inverse voltage permissible during the negative half-cycle depends on the kind of gas, its pressure, the distance between electrodes and the temperature of the anode.

The definitions and phenomena described so far should be sufficient to enable the operation of thyratrons to be understood, with which this article is specifically interested. In turning to these it may be pointed out that the majority of the subsequent definitions and data are also valid for all other rectifier tubes.

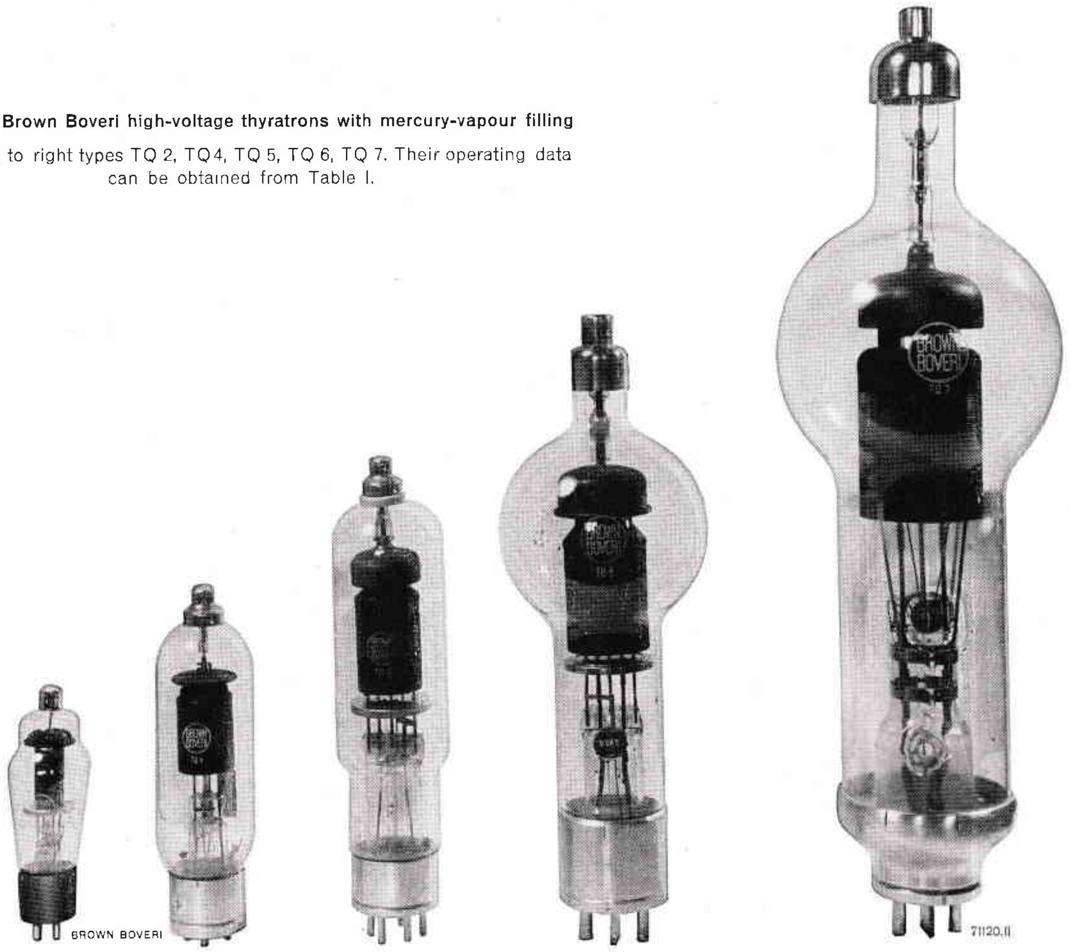


Fig. 1. — Brown Boveri high-voltage thyratrons with mercury-vapour filling

From left to right types TQ 2, TQ 4, TQ 5, TQ 6, TQ 7. Their operating data can be obtained from Table I.

Thyratrons

General

The construction of the thyratron (Fig. 1) differs from that of the rectifier tube just described, in that there is at least one additional electrode between the cathode and the anode. This is known as the control grid and consists usually of a perforated or slotted plate of sheet metal or graphite.

TABLE I

Thyratrons for High Anode Voltages

Type	Filament Voltage U_f V	Filament Current I_f A	Inverse Voltage U_{inv} kV	Mean Anode Current I_m A	Peak Anode Current I_{ap} A	Surge Current $I_{(0.1)}$ A	Integrating Time t_a s	Filling
TQ 2	2·5	7	7·5	0·5	2	25	15	Hg
TQ 4	5	7	10	1·25	5	50	15	Hg
TQ 5	5	10	15	1·75	7	70	15	Hg
TQ 6	5	18	20	2·5	10	100	15	Hg
TQ 7	5	22	20	5	20	400	15	Hg

If a sufficiently high d.c. voltage, negative with respect to the cathode, is applied to the control grid, only the odd electron will pass through the aperture to the anode. The magnitude of the resultant anode current will again be only a few microamperes and, by variation of the grid voltage, it can be regulated in the manner of the current in a high-vacuum triode. As the negative bias of the grid with respect to the cathode is reduced, an increasing number of less retarded electrons enter the space between grid and anode. When the grid voltage reaches a critical value, the energy of some electrons is sufficient to ionize the filler gas atoms. This sets in motion two processes. Firstly, the resultant positive ions begin to neutralize the existing electrons, which disperses the space-charge cloud and gives the remaining electrons higher mobility; thus the number of ionizing collisions increases. Secondly, in each collision between an electron and a gas atom further electrons are expelled from the atom and the number of electrons increases at a phenomenal rate. The tube fires and the voltage between anode and cathode collapses to the arc voltage. The anode current immediately rises sharply, limited only by the external resistance. At this moment the grid loses its control effect; any subsequent increase in the negative

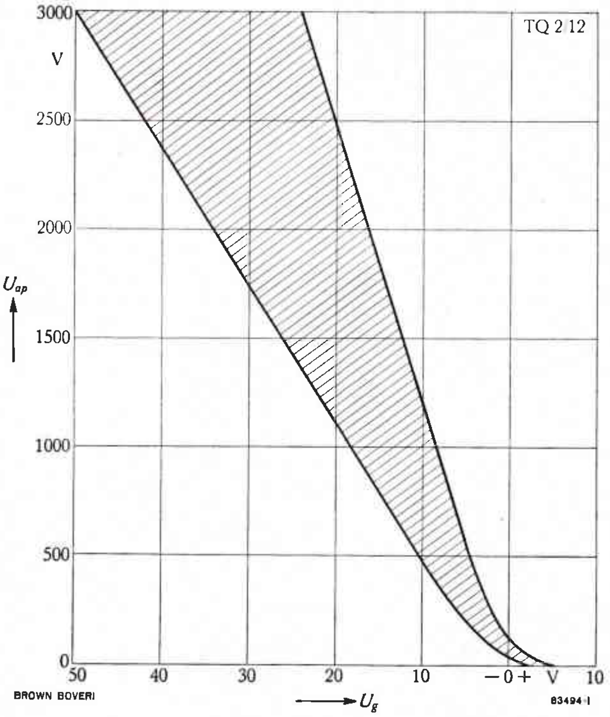


Fig. 2. — Firing curve of a mercury-vapour thyratron type TQ 2/12

U_{ap} = Maximum peak value of anode voltage in V
U_g = Grid voltage in V

The curve gives the relation between the anode and grid voltages necessary for firing. The shaded area represents the tolerance zone which is accounted for by temperature variation and unavoidable differences in individual tubes. Firing is impossible left of the shaded area, while to the right it is assured.

potential of the grid with respect to the anode has no further effect on the anode current and the tube no longer has the power to extinguish. The anode voltage must first fall below the arc voltage to extinguish the arc, which will not restrike until the anode voltage has risen above the firing voltage, the negative grid bias being also sufficiently small.

Fig. 2 indicates the relation between anode voltage and grid voltage (control characteristic or firing curve) in a Brown Boveri mercury-vapour thyratron type TQ 2/12 (Fig. 3). In keeping with standard practice, a definite characteristic line is not given but an entire zone (shaded), as all tubes of the same type will not fire at exactly the same anode and grid voltages. The zone illustrated is valid for the complete temperature interval within which a tube with a certain gas filling may be operated. Beyond the right-hand extremity of the shaded area the tube is certain to conduct and outside the left-hand extremity it will not.

The permissible temperature interval for the operation of mercury-vapour tubes is relatively restricted (25–60° C). The lower limit may prove a little high, especially in non-tropical countries, and cause the tube to take a long time to heat up, or even necessitate additional heating of the

TABLE II

Thyratrons for Medium Anode Voltages

Type	Filament Voltage U_f V	Filament Current I_f A	Inverse Voltage U_{inv} kV	Mean Anode Current I_m A	Peak Anode Current I_{ap} A	Surge Current $I_{(0.1)}$ A	Integrating Time t_a s	Filling
TQ 1/2	2·5	7	1·25	1·5	6	120	5	Hg + Ar
TQ 2/3	2·5	12	2	3·2	25	200	15	Hg
TX 2/3	2·5	12	1·5	3·2	40	560	15	Xe
TQ 2/6	2·5	22	2	6·4	40	600	15	Hg
TX 2/6	2·5	22	1·5	6·4	80	1120	15	Xe
TQ 2/12	2·5	33	2	12·5	100	1500	30	Hg

immediate vicinity of the tubes. If the tube should operate at too low a temperature, the arc voltage will increase due to the reduced vapour pressure, and invariably lead to early destruction of the emissive layer on the cathode. On the other hand, an excessively high vapour temperature causes the inverse voltage to diminish rapidly with resultant back-firing during the inverse phase which can prove destructive to the tube.

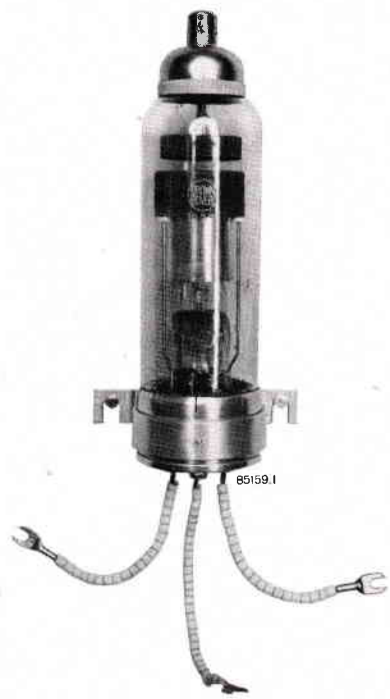


Fig. 3. — Thyratron TQ 2/12 filled with mercury vapour, rated for a maximum peak anode current of 100 A with a surge current of 1500 A and inverse voltage of 2000 V

See also Fig. 2 and Table II.

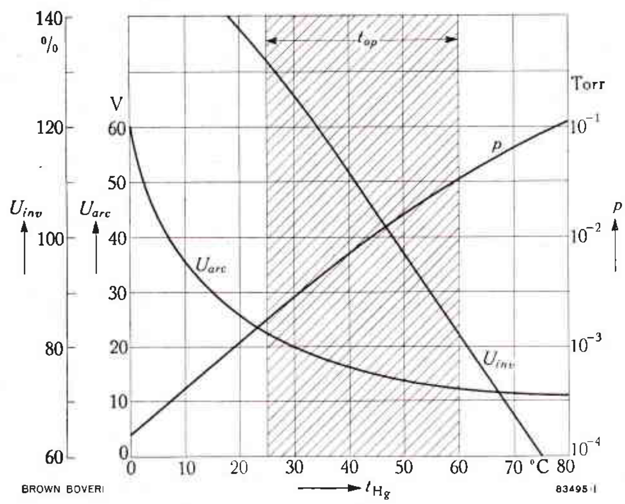


Fig. 4.—The effect of temperature on the data of mercury-vapour tubes

U_{inv} = Inverse voltage as a percentage of the most favourable value for the tube
U_{arc} = Arc voltage (V)
p = Mercury-vapour pressure (Torr)
t_{Hg} = Mercury temperature (°C)
t_{op} = Permissible temperature range for operation

Fig. 4 shows the variation of inverse voltage, arc voltage and vapour pressure with respect to the mercury-vapour temperature; the shaded area defines the permissible operating range. Depending on the ambient temperature, the mercury-vapour tubes must be preheated before applying the anode voltage; in most cases this can only be achieved with the cathode heating current. Where the external temperatures are too low the effect of the cathode heating current can be augmented by the gaseous discharge at a reduced anode voltage; this of course assumes that the anode voltage is capable of being varied. The correct heating conditions can be determined by measuring the bulb temperature at about 5 mm above the base. It is difficult to generalize here as too much depends on the influence of the surroundings. The filament heating times quoted in tube catalogues and data sheets merely indicate how long the cathode must be reheated after a brief interruption of the operating voltage (e.g. due to a short circuit) before re-applying the full anode voltage, always assuming that the tube is still warm to the touch when the cause of the interruption has been eliminated. In this respect, more favourable results are obtained with the hydrogen- or inert-gas-filled tubes, the properties of which will be discussed later.

Controllability

The anode circuit of a thyratron includes a load resistance and a source which provides the alternating anode voltage u_a (Fig. 5a). The firing curve z gives the negative grid bias, corresponding to the characteristic in Fig. 2, necessary for each value of anode voltage. If an alternating voltage u_g, dephased with respect to the anode voltage, is now applied to the grid, the tube fires at instant t_1; then the voltage between anode and cathode collapses to the value u_{arc}.

After time t_2, u_a becomes less than u_{arc} and the tube extinguishes. The anode current pulse is given by curve i_a, the resultant mean anode current being denoted by I_m. The displacement between the anode and grid voltages corresponds to angle $\varphi_1 < 90°$. Fig. 5b shows the same relationships, but for a displacement angle $\varphi_2 > 90°$. The mean anode current I_m is reduced in proportion to the duration of the pulse. It should be remembered that regulation is no longer possible when $\varphi > 180°$.

The displacement between anode and grid voltages can be caused by an inductance-resistance (*RL*) or capacitance-resistance (*RC*) network (*L* is preferably a variable inductor of the saturable-reactor type, in which a variable d.c. current flows).

The method of regulation described using phase control (Fig. 6) is frequently employed to advantage when accuracy in timing the firing point t_1 is not of crucial importance, which is usually the case when only the output current has to be controlled, as, for example, in the Brown Boveri Thyralux unit for dimming lighting installations containing fluorescent tubes [1].[1]

However, when t_1 has to be timed exactly, the method described is inadequate, because slight variation of the firing curve z—whether due to a change of tube or to a very variable ambient temperature—is immediately followed by displacement of the firing point.

In such cases, the method of control as shown in Fig. 5c is preferable, using firing pulses produced by an over-saturated leakage reactance transformer. The position of the pulse can be controlled very accurately, and even when the curve is considerably displaced (z', z'') the firing point t_1 does not change, provided the slope of the control pulse is sufficiently steep. This method of control is employed for example in the betatron [2]. The two most important methods of control already described (and others too [3]) allow the anode current to be varied steadily from zero to maximum value, during which process only the power of the forward period, corresponding to the mean d.c. current,

[1] The figures in brackets refer to the bibliography at the end of the article.

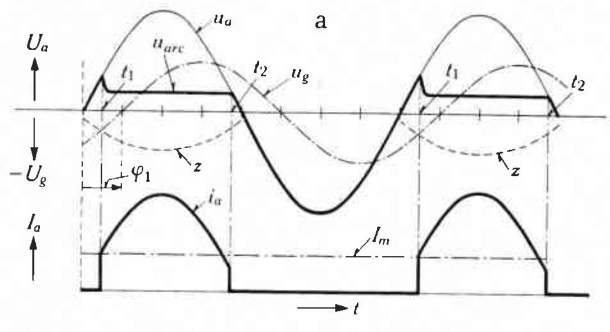


Fig. 5. — Methods of controlling the firing point of a thyratron, illustrated by anode voltage U_a or anode current I_a versus grid voltage U_g

u_a = Anode voltage
u_g = Grid voltage
u_{arc} = Arc voltage
i_a = Anode current impulse
I_m = Mean anode current
t = Time
t_1, t_3, t_4 = Firing points
t_2 = Extinction point
φ_1, φ_2 = Phase displacement between anode and grid voltages
z = Firing curve
z', z'' = Deviations of firing point

a and b: Mean anode current I_m, controlled by alternating grid voltage u_g having a phase displacement with respect to the anode voltage u_a. Curve a refers to a heavy anode current I_m, curve b to a low value.
c: Control by pulses on grid with heavy negative bias. The curve shows the control of two firing points t_3 and t_4.

is taken from the a.c. voltage source, and no losses occur in the thyratron itself during the inverse period.

Special Properties of Thyratrons

Some details of thyratrons will now be mentioned, the knowledge of which may avoid inconvenience to the user. The data sheets usually give the maximum values of the following quantities: peak anode current I_{ap}, mean anode current I_m and averaging time t_a.

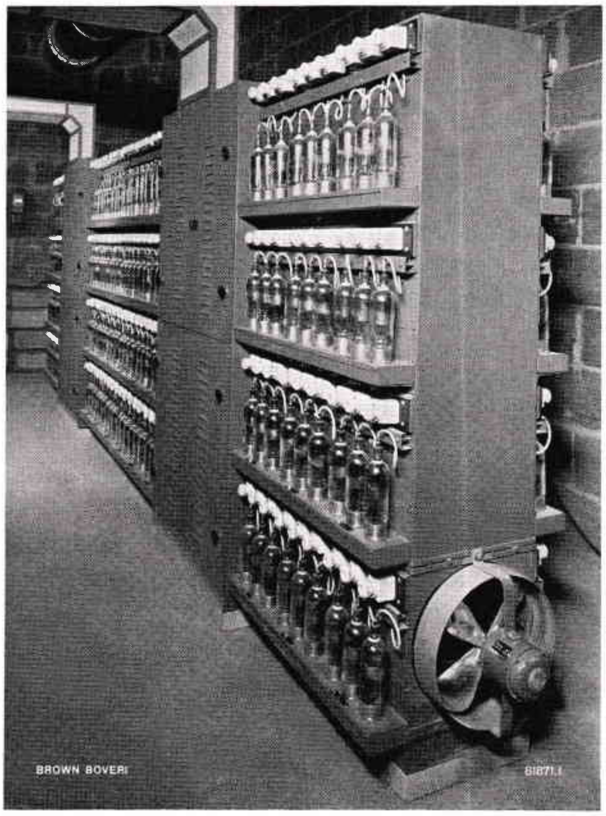


Fig. 6. — A large electronic stage-lighting dimmer

Employing Brown Boveri type TQ 2/6 mercury-vapour thyratrons.

The design of cathodes used in Brown Boveri thyratrons, in respect of heating power and surface treatment, is such that they can stand the maximum peak value of the anode current continuously without the arc voltage increasing to a level likely to damage the tube. But as the anode possesses a limited heat capacity and can only radiate or conduct a limited amount of heat, no more than the maximum value of the mean anode current should be permitted to flow in the tube for an unlimited time. Furthermore, it will prevent deterioration of the cathode if, while keeping the mean anode current within the permissible limits, the maximum peak value is not exceeded.

During continuous operation, therefore, it is advisable to measure the mean anode current with a d.c. ammeter and to determine the peak value with a cathode-ray oscillograph, as the relation between these two quantities is a function of the pulse wave-form, which itself is closely related to the nature of the load on the anode circuit. If, however, the operation of the tube is intermittent, such as may be the case with electronically controlled welders [4],

the averaging time t_a—i.e. from the start of one train of pulses to the start of the next—will have a definite bearing on the relation between the peak value of the anode current I_{ap} and the mean value I_m.

Assuming an alternating voltage at 50 c/s and an inductive load, let us suppose that intermittent operation is specified for a time t_x with current pulses I_x, having an approximately square wave-form and a width of one half-cycle. Then the following relationships hold good:

$$\tfrac{1}{2}\, I_x\, t_x = I_m\, t_a \qquad (1)$$

and

$$I_x \leq I_{ap} \qquad (2)$$

(the factor $\frac{1}{2}$ is introduced because the tube only fires during the positive half-wave).

For the Brown Boveri thyratron type TQ 2/6, for instance

$$I_{ap} = 40\ \mathrm{A};\ I_m = 6{\cdot}4\ \mathrm{A};\ t_a = 15\ \mathrm{s}.$$

For $I_x = 40$ A (that is when $I_x = I_{ap}$, which is permissible according to eq. 2), $t_x = 6{\cdot}4 \times 15 \times 2/40 = 4{\cdot}8$ s, which means that the tube may be subjected to square-wave pulses of 40 A for 4·8 s, after which an interval of $15 - 4{\cdot}8 = 10{\cdot}2$ s must be allowed, before the train of pulses is repeated.

For $I_x = 20$ A, t_x would be 9·6 s and the interval at least 5·4 s. For $I_x = 12{\cdot}8\ \mathrm{A} = 2\, I_m$, $t_x = t_a = 15$ s and the interval = 0 s. This is in effect continuous operation, because this pulse train represents a mean anode current of 6·4 A during the whole of the prescribed averaging time.

If for example I_x is chosen equal to 60 A, then $t_x = 6{\cdot}4 \times 15 \times 2/60 = 3{\cdot}2$ s and the interval 11·8 s. From eq. (1) this appears to be perfectly permissible for the anode, but eq. (2) forbids $I_x > I_{ap}$ to prevent deterioration of the cathode. Thus operation with peaks of this height is not permissible, despite the short time t_x.

Tube users would therefore be well advised to obtain all available information concerning pulse times and mean anode currents.

In the event of short circuits in the anode circuit of a tube a further quantity, to be found in all data sheets, is important, i.e. the surge current $I_{(0\cdot1)}$. The figure in brackets denotes the maximum time in seconds during which a given current surge can be tolerated. As all such surges damage the cathode to some extent, they should be avoided wherever possible and in any case one should ensure that the protective relays respond within the stipulated time.

Fig. 7. — Brown Boveri tubes filled with inert gas

Right, a type TX 2/6 thyratron built to carry 6·4 A continuously; centre, type TX 2/3, also filled with xenon and rated 3·2 A continuously. The tube on the left is a 10-kV hot-cathode half-wave rectifier of the DX 2 type.

Inert-Gas-Filled Tubes

Due to the fact that the operating temperature has a considerable effect on the firing of tubes filled with mercury vapour, besides which the permissible range of temperature variation is very restricted, thyratrons filled with an inert gas were introduced. These gases have the advantage that their pressure varies only very slightly with temperature and, in consequence the firing curve remains constant throughout a very wide temperature range. Moreover, the heating time is considerably reduced compared with mercury-vapour tubes, as only the cathode now has to be heated to the correct operating temperature. Tubes with inert gas filling can also be mounted in any position. A point of criticism is, perhaps, that the inverse voltage is somewhat lower, although for industrial purposes this is of subordinate significance.

The manufacturer is confronted with the problem of absorption of the filler gas by the anode during the inverse phase, which steadily reduces the gas pressure during the life of the tube, leading to premature breakdown. Enclosing the anode almost completely in a metal sheath, which is arranged to be at cathode potential, goes a long way towards overcoming this difficulty. Brown Boveri are now producing a range of xenon-filled thyratrons which are also

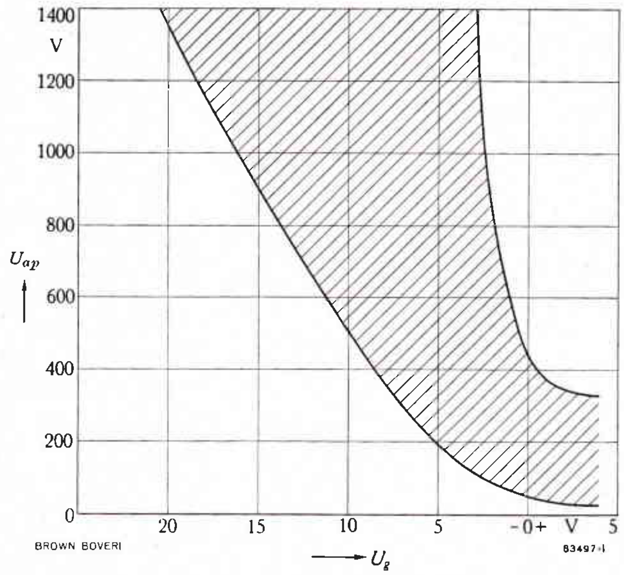


Fig. 8. — Firing curve of a type TX 2/6 xenon-filled thyratron

U_{ap} = Peak anode voltage in V
U_g = Grid voltage in V

proving quite successful as far as their life is concerned and can replace mercury-vapour tubes in any situation where the demands in respect of ambient temperature are particularly severe (Fig. 7 and 8).

The xenon tubes can be employed to advantage, for example, in locomotives and aircraft, in rectifying or regulating gear installed in unheated areas or out-of-doors, in countries where air temperatures are low or subject to violent fluctuation. The permissible working range is from $-70°$ to $+90°C$, in addition to which these tubes can operate up to a frequency of 400 c/s, whereas the mercury-vapour tubes are limited to approximately 150 c/s, this being governed by the rate of deionization during the inverse phase. A further advantage is the favourable relation between the maximum peak value and the maximum mean value of the anode current, which in the case of the xenon tube is approximately 12:1, against only 8:1 in mercury-vapour tubes. These advantages certainly compensate for their life being slightly shorter than that of mercury-vapour tubes.

As a compromise the same tube can be filled with a mixture of mercury-vapour and inert gas, for instance argon. When cold this tube functions exactly as an inert gas tube, but as the temperature rises it assumes the characteristic of the mercury-vapour discharge. The increased life of modern inert-gas-filled tubes tends to make them more economical, which is likely to cause the gas-mercury tube to lose some of its original significance.

TABLE III

Rectifier Tubes

Type	Filament Voltage U_f V	Filament Current I_f A	Inverse Voltage U_{inv} kV	Mean Anode Current I_m A	Peak Anode Current I_{ap} A	Surge Current $I_{(0.1)}$ A	Filling
DQ 2	2·5	5	10	0·25	1	20	Hg
DX 2	2·5	5	10	0·25	1	20	Xe
DQ 4	5	7	10	1·25	5	50	Hg
DQ 5	5	10	20	1·75	7	70	Hg
DQ 6	5	18	20	2·5	10	100	Hg
DQ 7	5	30	22	5	20	400	Hg

Tube Data

The various types of thyratrons produced by Brown Boveri are listed in Tables I, II and III, particular attention being merited by the medium-voltage tubes, which are primarily intended for use in industry. To complete the list, the high-voltage thyratrons used mainly in transmitters, and rectifier tubes are also included.[1] Further additions to the range will of course be made, and mean anode currents of the order of 25 A are anticipated.

MS 822 (KME) *W. Lüdy*

[1] The reader will find further details in the Brown Boveri handbook "Electronic Tubes", or in the data sheets supplied with each tube. Additional examples of the application of thyratrons are described in earlier issues of this journal [5, 6, 7].

Bibliography

[1] R. Hübner: Gasgefüllte Elektronenröhren und ihre Anwendungsmöglichkeit. Bull. schweiz. elektrotech. Ver. 1953, Vol. 44, No. 13, p. 560–6.

[2] R. Wideröe: The 31-MeV Ray Transformer (Betatron). Brown Boveri Rev. 1951, Vol 38, No. 9/10, p. 260–72.

[3] R. Hübner: Das Thyratron als Schalt- und Regelröhre. Bull. schweiz. elektrotech. Ver. 1952, Vol. 43, No. 19, p. 760–4.

[4] E. Gut: Combinable Electronic Controls for Air-Operated Heavy-Duty Spot Welding Machines. Brown Boveri Rev. 1952, Vol. 39, No. 4, p. 135–40.

[5] G. Wetten: Inertia-Free Control of Continuous Rolling Mill Drives. Brown Boveri Rev. 1952, Vol. 39, No. 4, p. 114–8.

[6] A. Goldstein: Contact Rectifier Switching Problems. Brown Boveri Rev. 1950, Vol. 37, No. 12, p. 478–88.

[7] R. Hübner: Thyratrons for Industrial Applications. Brown Boveri Rev. 1953, Vol. 40, No. 9, p. 354–7.

Publications on Mutators by Brown Boveri and Associated Authors

016:621.314.65

1938

C. Brynhildsen: Mutators with Metal Tanks and Forced Air-Draught Cooling. Brown Boveri Rev. 1938, Vol. 25, No. 12, p. 261-4.

A. E. Danz: Das selbsttätige Gleichrichter-Unterwerk Alpnachstad der Pilatusbahn. Elekt. Bahnen 1938, Vol. 14, No. 9, p. 224–6.

E. F. Fässsler: Die Stromoberwellen auf der Wechselstromseite von Stromrichtern. Arch. Elektrotech. 1938, Vol. 32, No. 10, p. 640–54.

W. E. Gutzwieler: Rectifiers adopted for American Aluminium. Elect. Wld 1938, Vol. 110, 3rd, Dec., p. 1585 (41)–1588 (44).

H. Hutt: Die BBC-Gleichrichterlokomotive für die Höllentalbahn. BBC-Nachr. 1938, Vol. 25, No. 4, p. 123–34.

D. Journeau: What goes on in the Mercury Arc Rectifier. Allis-Chalmers elect. Rev. 1938, Vol. 3, No. 4, p. 9–16.

O. Keller: Steel Tank Mercury Arc Rectifiers for Low Power Applications. Pwr Plant Engng 1938, Vol. 42, No. 11, p. 712–16.

E. Kern: Der Dreiphasen-Stromrichtermotor und seine Steuerung bei Betrieb als Umkehrmotor. Elektrotech. Z. 1938, Vol. 59, No. 18, p. 467–70; No. 19, p. 494–7.

E. Kobel: The Voltage Drop in the Arc and the Gradient in the Positive Column in the Direct-Current Mercury Arc. Brown Boveri Rev. 1938, Vol. 25, No. 8, p. 171–5.

J. Kübler: Ueber die Messung der Einzelverluste bei Mutator-Transformatoren. Bull. schweiz. elektrotech. Ver. 1938, Vol. 29, No. 11, p. 273–81.

F. A. Lauper: Parallel Operation of Mercury Arc Rectifiers and Rotating Machinery. Allis-Chalmers elect. Rev. 1938, Vol. 3, No. 3, p. 14–19.

O. K. Marti: New Fields for Mercury Arc Rectifiers. Power 1938, Vol. 82, No. 1, p. 16–18.

V. De Martini: Gli impianti di alimentazione del centro radiofonico ad onde medie di Roma-Santa Palomba. Rass. tec. TIBB 1938, Vol. 3, No. 2, p. 24–9.

V. De Martini: Innovazione negli impianti della ferrovia Torino-Lanzo-Cères. Rass. tec. TIBB 1938, Vol. 3, No. 1, p. 14–17.

V. De Martini: Piccole sottostazioni automatiche per l'alimentazione di tranvie e filovie. Rass. tec. TIBB 1938, Vol. 3, No. 3, p. 41–9.

R. Risch: Der Quecksilberdampfdruck in Mutatoren, Bauart Brown Boveri. Bull. schweiz. elektrotech. Ver. 1938, Vol. 39, No. 23, p. 646–54.

1939

W. Bauer: Die Entwicklung der durch Stromrichter gesteuerten Walzwerkantriebe Stahl und Eisen 1939, Vol. 59, p. 196.

S. R. Durand: A Mercury Arc Static Inverter. Allis-Chalmers elect. Rev. 1939, Vol. 4, No. 3, p. 25–30.

P. Egloff: The First 50000 Volt Direct-Current Power Transmission by means of Mutators. Brown Boveri Rev. 1939, Vol. 26, No. 4/5, p. 92–6.

P. Egloff and J. J. Felix: La première transmission d'énergie électrique par courant continu 50000 V à l'aide de mutateurs. Electricité 1939, Vol. 23, No. 59, p. 237.

C. Ehrensperger: The Flexible Coupling of Systems by means of Mutators Restores his Independence to the Operator, while Increasing the Economical Operation of the Systems. Brown Boveri Rev. 1939, Vol. 26, No. 4/5, p. 117–20.

C. Ehrensperger: Mutatoren. Bull. schweiz. elektrotech. Ver. 1939, Vol. 30, No. 18, p. 548–53.

D. Journeau: Rectifiers in Reverse. Allis-Chalmers elect. Rev. 1939, Vol. 4, No. 3, p. 20–4.

E. Kern: Die Drehstrom-Drehstrom-Mutatoranlage Lütschental der Jungfraubahn. Bull. schweiz. elektrotech. Ver. 1939, Vol. 30, No. 9, p. 225–29.

E. Kern: Die Gleichstrom-Kraftübertragung Wettingen–Zürich an der Schweiz. Landesausstellung. Bull. schweiz. elektrotech. Ver. 1939, Vol. 30, No. 17, p. 481–2.

E. Kern: Die Gleichstrom-Kraftübertragung, ihr heutiger Stand und ihre Zukunft. Bull. schweiz. elektrotech. Ver. 1939, Vol. 30, No. 18, p. 567–70.

V. De Martini: I mutatori negli impianti di laminatoi. Energia elett. 1939, Vol. 16, No. 2, p. 125–37.

V. De Martini: La ferrovia elettrica Casalecchio-Vignola. Rass. tec. TIBB 1939, Vol. 4, No. 3, p. 54–61.

V. De Martini: Il convertitore statico di frequenza nel collegamento di reti trifasi indipendenti. Rendiconti della AEI, Bologna 1939. Memoria 112.

W. Nowag: Drehzahlregelung mit gittergesteuerten Stromrichtern. Z. Ver. dtsch. Ing. 1939, Vol. 81, p. 827.

1940

S. R. Durand: The Excitron. Allis-Chalmers elect. Rev. 1940, Vol. 5, No. 2, p. 9–15.

L. S. Dzung: Anwendung der Methode der symmetrischen Komponenten zur Berechnung eines Gleichrichters. Arch. Elektrotech. 1940, Vol. 34, No. 7, p. 408–15.

E. Fässler: Der Einfluss der Oberwellen im Drehstromnetz auf die Harmonischen der Gleichspannung und des Netzstromes von Gleichrichtern. Arch. Elektrotech. 1940, Vol. 34, No. 4, p. 209–29.

E. Fässler: Ueber die Wirkungsweise des Drehstrom-Drehstrom-Mutators. Bull. schweiz. elektrotech. Ver. 1940, Vol. 31, No. 2, p. 34–40.

A. Leuthold: Brown Boveri's Overseas Pioneering Work in the Field of Heavy-Current Mutators for Electrolysis. Brown Boveri Rev. 1940, Vol. 27, No. 10, p. 191–7.

O. K. Marti: Wave Shape of 30- and 60-Phase Rectifier Groups. Trans. Amer. Inst. elect. Engng 1940, Vol. 59, No. 4, p. 218–24.

O. K. Marti: Network Coupling by means of Static Electronic Frequency Changers. Trans. Amer. Inst. elect. Engng 1940, Vol. 59, No. 9, p. 495–502.

V. De Martini: Il primo impianto in Italia di mutatori in cassa metallica. Rass. tec. TIBB 1940, Vol. 5, No. 4, p. 73–4.

V. De Martini: Gli impianti delle filovie comensi. Rass. tec. TIBB 1940, Vol. 5, No. 5, p. 82–91.

F. Mertens: Eine Gleichrichteranlage für 80 000 A bei 800 V zum Betrieb einer Elektrolyse. BBC-Nachr. 1940, Vol. 27, No. 1, p. 1–11.

1941

W. Deck: Vapour Currents in the Anode Sleeves of Mutators and their Influence on the Operating Conditions of the Mutator. Brown Boveri Rev. 1941, Vol. 28, No. 4/5, p. 97–108.

M. Demontvignier: Essai d'une théorie de l'ionisation résiduelle dans l'arc à mercure. Conséquences pratiques sur le fonctionnement des redresseurs. Rev. gén. élect. 1941, Vol. 50, No. 10, p. 239–55.

C. Ehrensperger: Comparison on an Economical Basis of A. C. and D. C. Power Transmission over Long Distances. Brown Boveri Rev. 1941, Vol. 28, No. 10 p. 249–63.

A. Gaudenzi: High-Vacuum Mutators for Direct-Current Transmission. Brown Boveri Rev. 1941, Vo. 28, No. 10, p. 319–22.

A. Goldstein: Die Berechnung des selbstgeführten, fremdgesteuerten Sechsphasen-Gleichstrom-Drehstrom-Mutators. Bull. schweiz. elektrotech. Ver. 1941, Vol. 32, No. 23, p. 614–22.

H. Keller: The High-Power Mutator for Direct-Current Power Transmission. Brown Boveri Rev. 1941, Vol. 28, No. 10, p. 322–5.

E. Kern: Transformer Connections for High-Voltage D. C. Power Transmission. Brown Boveri Rev. 1941, Vol. 28, No. 10, p. 314–9.

P. Lauener: The Layout of the Terminal Station for High-Voltage Transmission. Brown Boveri Rev. 1941, Vol. 28, No. 10, p. 325–9.

G. P. Spolverini: Impiego dei mutatori per l'alimentazione dei forni ad alta frequenza. Rass. tec. TIBB 1941, Vol. 6, No. 4, p. 57–63.

1942

W. Deck: Strömungen von Quecksilberdampf in den Anodenhülsen von Mutatoren. Helv. phys. Acta 1942, Vol. 40, p. 273–306.

W. Deck: The Adsorption of Gases by the Steel Walls of Vacuum Discharge Apparatus and Its Bearing on the Life of Pumpless Mutators. Brown Boveri Rev. 1942, Vol. 29, No. 8, p. 202–4.

G. De Francesco and F. Martinelli: I mutatori a vapore di mercurio nel quadro generale dell'autarchia. Rendiconti della AEI, Firenze 1942. Memoria 167, p. 404–8.

V. De Martini: Sottostazioni mobili con mutatori nella piccola trazione. Rass. tec. TIBB 1942, Vol. 7, No. 1, p. 7–12.

M. Rossé: Remote Control Simplifies Operation. Brown Boveri Rev. 1942, Vol. 29, No. 11/12, p. 376–7.

P. Waldvogel: Additional Losses in Transformers and Machines feeding Mutators. Brown Boveri Rev. 1942, Vol. 29, No. 11/12, p. 357–73.

1943

M. Demontvignier: Possibilité de génération de puissance réactive dans les onduleurs. Rev. gén. Elect. 1943, Vol. 52, No. 1, p. 19–32.

E. Kern: A 3000-kW Mobile Mutator Substation for Traction Service and Regenerative Braking Duty. Brown Boveri Rev. 1943, Vol. 30, No. 5/6, p. 110–3.

F. Mertens: Kurzschlussschutz und Kurzschlussfortschaltung in Stromrichteranlagen. BBC-Nachr. 1943, Vol. 30, No. 1, p. 1–13.

A. Odermatt: Pumpless Mutator operates 14 000 Hours without Backfire. Brown Boveri Rev. 1943, Vol. 30, No. 5/6, p. 124–5.

S. Widmer: The Brown Boveri Pumpless Air-Cooled Mutator. Brown Boveri Rev. 1943, Vol. 30, No. 7/8, p. 199–202.

1944

C. Brynhildsen: The Evolution of the Brown Boveri Air-Cooled Mutator. Brown Boveri Rev. 1944, Vol. 31, No. 7, p. 215–21.

C. Brynhildsen: Swiss Mutator Plants Then and Now. Brown Boveri Rev. 1944, Vol. 31, No. 7, p. 237–8

A. Danz: New Mutator Plants in the Swiss Metallurgical and Chemical Industries. Brown Boveri Rev. 1944, Vol. 31, No. 4, p. 131–8.

C. Ehrensperger: Tenth Anniversary of Introduction of Term "Mutator". Brown Boveri Rev. 1944, Vol. 31, No. 12, p. 402–4.

P. Lauener: The Advantages of Pumpless Mutator Plants in Traction Substations. Brown Boveri Rev 1944, Vol. 31, No. 3, p. 110–12.

P. Lauener: Three Years' Trial of Pumpless Air-Cooled Mutator in Traction Operation. Brown Boveri Rev. 1944, Vol. 31, No. 11, p. 379–80.

A. Odermatt: Les Chevalleyres Pumpless Mutator Substation. Brown Boveri Rev. 1944, Vol. 31, No. 8, p. 273–4.

1945

C. Brynhildsen: Present Mutator Construction for Direct-Current High-Voltage Transmission. Brown Boveri Rev. 1945, Vol. 32, No. 9, p. 318–21.

M. Demontvignier: Harmoniques irréguliers de la tension continue des redresseurs et onduleurs. Rev. gén. Elect. 1945, Vol. 54, No. 3, p. 89–93.

M. Demontvignier: Réglage de la vitesse d'un moteur à courant continu alimenté par mutateur à grilles commandées. Bull. Soc. franç. Elect. Series 6, 1945, Vol. 5, No. 9, p. 262–5.

C. Ehrensperger: Comparative Study of Some Problems of A.C. and D.C. Power Transmission. The D.C. Transmission Ready for Practical Application. Brown Boveri Rev. 1945, Vol. 32, No. 9, p. 284–95.

C. Ehrensperger: Operating Problems concerning Future D.C. High-Voltage Transmission Systems. Brown Boveri Rev. 1945, Vol. 32, No. 9, p. 322–4.

H. Keller: Latest Developments Bring First Direct-Current High-Voltage Transmission with Mutators in Sight. Brown Boveri Rev. 1945, Vol. 32, No. 9, p. 310–18.

P. Lauener: Layout of a Terminal Station for Direct-Current Transmission. Brown Boveri Rev. 1945, Vol. 32, No. 9, p. 306–9.

P. Rossi: Instalaciones de mutatores en America del Sur. Suiza Técnica 1945, Vol. 24, No. 1, p. 57–8.

P. Waldvogel: Le problème du transport d'énergie électrique à grande distance à la lumière de quelques travaux récents. Bull. schweiz. elektrotech. Ver. 1945, Vol. 36, No. 4, p. 105–15.

1946

C. Brynhildsen: Recommissioning the Dutch Railways. Brown Boveri Rev. 1946, Vol. 33, No. 9, p. 246–8.

C. Ehrensperger: Fernübertragung mit hochgespanntem Gleichstrom. Neue Zürcher Ztg 1946, No. 124.

C. Ehrensperger: Direct-Current Transmission. Brown Boveri Rev. 1946, Vol. 33, No. 10, p. 294–7.

C. Ehrensperger: Present-Day Problems of D.C. Long-Distance Transmission. Brown Boveri Rev. 1946, Vol. 33, No. 10, p. 298–9.

E. Fässler: Ein Streifzug durch die netzseitigen Spannungen und Ströme von Mutatoren. Bull. schweiz. elektrotech. Ver. 1946, Vol. 37, No. 23, p. 677–88.

J. Inglin: The Pumpless Mutator Plants in Switzerland. Brown Boveri Rev. 1946, Vol. 33, No. 6/7, p. 149–51.

S. Rump: Kraftoverføring af meget store Effekter over lange Afstange. Ingeniøren 1946, Vol. 55, No. 1, p. E1, and Elektroteknikeren 1946, Vol. 59, p. 49 and 65.

S. Rump: Discussion on "Kraftöverföring med högspänd Likström". Tekn. Tidskr. 1946, Vol. 76, p. 975–6.

1947

M. Demontvignier: Compensation des harmoniques primaires des redresseurs en grande traction par déphasage des sous-stations. Rev. gén. Elect. 1947, Vol. 56, No. 7, p. 301–10.

M. Hürlimann: Connection and Number of Phases of A.C.–D.C. Mutator Plants with Special Regard to the Harmonics in the Direct Voltage and Primary Current. Brown Boveri Rev. 1947, Vol. 34, No. 10/11, p. 200–8.

T. Wasserrab: Die Beeinflussung der positiven Säule durch ein magnetisches Querfeld. Z. Naturforsch. 1947, Vol. 2a, p. 575–82.

1948

M. Demontvignier: Atténuation des harmoniques renvoyés au réseau d'alimentation par les redresseurs de grande traction. Bull. Soc. franç. Elect. Series 6, 1948, Vol. 8, No. 78, p. 61–71.

M. Demontvignier: Conditions de coexistence locale de mutateurs et de dispositifs de télécommande "Actadis". Rev. gén. Elect. 1948, Vol. 57, No. 6, p. 241–5.

P. Lauener: 90000-A Mutator Plant in an Aluminium Works. Brown Boveri Rev. 1948, Vol. 35, No. 11/12, p. 314–6.

E. Kobel: Zusammenhang zwischen der Benetzung und dem elektrischen Uebergangswiderstand zwischen Eisen und Quecksilber. Schweiz. Arch. f. angew. Wiss. u. Tech. 1948, Vol. 14, No. 11, p. 326–30.

R. Risch: Die Berechnung von Molekularvakuumpumpen. Schweiz. Arch. f. angew. Wiss. u. Tech. 1948, Vol. 14, No. 9, p. 279–85.

S. Rump: Forsynnig av Jylland og Fyn med elektrisk Kraft fra Sydnorge. Elektroteknikeren 1948, No. 22, p. 697.

1949

O. Keller: How to use Mercury Arc Rectifiers. Fact. Mgmt Mainten. 1949, Vol. 107, No. 2, p. 103–9.

W. Nowag: Der pumpenlose Eisengleichrichter. BBC (Mannheim) Publication, Gr. 1077/S, Dec. 1949.

1950

H. Bauer: Fortschritt durch Stromrichterantrieb für schwere Umkehr-Walzenstrassen. Stahl u. Eisen, 1950, Vol. 70, No. 3, p. 90–6.

H. Meyer-Delius: BBC und die Entwicklung der Stromrichter. BBC-Nachr. 1950, Vol. 32, No. 1, p. 47–55.

W. Ostendorf: Stromrichteranlagen in Eingefässschaltung für Umkehrwalzenstrassen. Elektrotech. Z. 1950, Vol. 71, No. 6, p. 137–41.

T. Wasserrab: Die Energieübertragung durch Elektronenstoss im Quecksilberdampfplasma. Z. Phys. 1950, Vol. 127, p. 324–33.

T. Wasserrab: Zur Theorie der Doppelschichten in Niederdruckgasentladungen. Z. Phys. 1950, Vol. 128, p. 575–85.

1951

K. Aymanns: Stromrichter für Industrie-Regelantriebe. BBC (Mannheim) Publication, Gr 1083/S, Apr. 1951.

W. M. de Boor: Certain Aspects of the Application of Mercury Arc Rectifiers of Large Outputs and of the Mechanical Rectifier. J. Instn cert. Engrs S. Afr. 1951, Vol. 24, No. 5, p. 109–123, No. 6, p. 129–51.

M. Demontvignier: Le mécanisme de l'étouffement par grilles des courts-circuits dans les redresseurs. Rev. gén. Elect. 1951, Vol. 60, No. 4, p. 147–54.

M. Demontvignier: La consommation de puissance réactive par le circuit continu dans les redresseurs et onduleurs. Rev. gén. Elect. 1951, Vol. 60, No. 12, p. 509–16.

F. V. Gilardi: Impiego di mutatori a vapore di mercurio negli impianti di elettrolisi e negli impianti di laminatoi. Rendiconti della AEI, Firenze 1951, Memoria 209.

H. Meyer-Delius and W. Nowag: Stromrichter. In E. v. Rziha: Starkstromtechnik. 8th Ed. 1951.

T. Wasserrab: Zur Beschreibung von Quecksilberdampfströmungen mit Ueberschallgeschwindigkeit. BBC-Nachr. 1951, Vol. 33, No. 1, p. 3–8; No. 2, p. 35–44.

T. Wasserrab: Vakuumtechnische Fortschritte im Stromrichterbau. BBC-Nachr. 1951, Vol. 33, No. 4, p. 127–37.

T. Wasserrab: Die Spritzentladung, eine Rückzündungsursache der Quecksilberdampf-Stromrichter. Arch. Elektrotech. 1951, Vol. 40, No. 3, p. 171–7.

T. Wasserrab: Fortschritte in der Erforschung der Stromrichter-Gasentladungen. VDE-Fachber. 1951, Vol. 15, p. 305–9.

T. Wasserrab: Die Neutralgaserwärmung der Niederdruckgasentladung. Z. Phys. 1951, Vol. 129, p. 190–201.

T. Wasserrab: Zur Theorie des Quecksilberkathodenflecks. Z. Phys. 1951, Vol. 130, p. 311–20.

1952

C. Alfisi and A. Molinari: La nuova filovia Torino–Chieri. Rass. tec. TIBB 1952, Vol. 13, No. 3, p. 49–67.

L. Collin: Sous-station de grande traction Paris–Lyon, Inform. CEM 1952, No. 15, p. 23–32.

M. Demontvignier: Méthodes générales de calcul des onduleurs autonomes. Rev. gén. Elect. 1952, Vol. 61, No. 6, p. 271–8.

C. Ehrensperger: High-Voltage Direct Current, the Swiss Viewpoint. Direct Current 1952, Vol. 1, No. 1, p. 22–6.

J. Inglin: Brown Boveri Mutators at Copenhagen. Brown Boveri Rev. 1952, Vol. 39, No. 10, p. 394–5.

G. Lemcke: Die Regelung der kontinuierlichen Walzenstrassen. VDE-Fachber. 1952, Vol. 16, p. IV/18–IV/22.

H. Schirmer: Stromrichtergesteuerte Antriebe im Gebiet höherer Leistungen. BBC-Nachr. 1952, Vol. 34, No. 2, p. 62–71.

T. Wasserrab: Der Gradient der positiven Säule im Quecksilberdampf. Z. Phys. 1952, Vol. 133, p. 532–6.

1953

W. M. de Boor: The 3000-kW Air-Cooled Mutator Sets of the South African Railways. Brown Boveri Rev. 1953, Vol. 40, No. 11/12, p. 470–5.

M. Demontvignier: Les possibilités de réalisation des mutateurs à grand nombre de phases. Bull. Soc. franç. Elect. Series 6, 1953, Vol. 3, No. 30.

G. Lemcke: Elektronische und magnetische Regelverfahren in kontinuierlichen und Umkehr-Warmwalzwerken. Stahl u. Eisen 1953, Vol. 73, No. 18, p. 1156–61.

E. H. Ludwig: Weiterführung der Theorie der positiven Niederdrucksäule I. Z. angew. Phys. 1953, Vol. 5, No. 10, p. 377–86.

A. Odermatt: Stand des Gleichrichterbaues bei BBC. Tech. Rdsch. 1953, Vol. 45, No. 11, p. 17–18.

1954

W. Besthorn: Der Rapid-Gittersteuersatz, eine entscheidende Verbesserung im Regelkreis. BBC-Nachr. 1954, Vol. 36, No. 3, p. 88–92.

W. Kleinmann: Die Entwicklung des Kontistrassen-Antriebs mit Stromrichterspeisung. BBC-Nachr. 1954, Vol. 36, No. 3, p. 105–9.

G. Lemcke: Neue Möglichkeiten der Steuerung von Kaltband-Walzwerken bei Speisung durch Stromrichter. BBC-Nachr. 1954, Vol. 36, No. 3, p. 121–4.

H. Lisner: Elektronische Regelung kontinuierlicher Warmwalzwerke. BBC-Nachr. 1954, Vol. 36, No. 3, p. 110–14.

E. H. Ludwig: Neuere Entwicklungen auf dem Gebiete der stromrichtergespeisten Grossantriebe. VDE-Fachber. 1954, Vol. 18, p. III/50–III/55.

E. H. Ludwig: Die jüngste Entwicklung der Umkehrsteuerungen bis zur Feldreversierung. BBC-Nachr. 1954, Vol. 36, No. 3, p. 93–7.

E. H. Ludwig: Das Kontiflux-Verfahren für Kaltband-Walzwerke. BBC-Nachr. 1954, Vol. 36, No. 3, p. 125–8.

W. Nowag: Fortschritte in der Bahnstromversorgung durch Stromrichter. Elektr. Bahnen 1954, Vol. 25, p. 124–34.

W. Ostendorf: Stromrichter für die Industrieantriebe. Elektropost 1954, No. 11, p. 177–80.

W. Ostendorf: Entwicklung der Stromrichterantriebe für Reversier-Walzwerke. BBC-Nachr. 1954, Vol. 36, No. 3, p. 83–7.

T. Wasserrab: Neuere Untersuchungen an Quecksilberdampf-Stromrichtern. VDE-Fachber. 1954, Vol. 18, p. III/46–III/50.

T. Wasserrab: Neuere Untersuchungen an Quecksilberdampf-Stromrichtern. Tech. Rdsch. 1954, Vol. 46, No. 44, p. 5.

T. Wasserrab: Die statistischen Gesetzmässigkeiten der Mutatorrückzündungen. Sci. Elect. 1954, Vol. 1, No. 3, p. 112–26.

Brown Boveri Electrical Products

Generators, Transformers

Mutators, Contact Converters, Motor-Generators

Emergency Sets

Protection and Regulating Gear

Air-Blast and Convector (L.O.C.) Circuit-Breakers

On-Load Isolating Switches, Industrial Switchgear

Direct-Current, Synchronous and Induction Motors

Three-Phase Shunt Commutator Motors

Electronically Controlled Drives

Arc and Resistance Welding Plants

Electric Furnaces, Electronic Generators

Transmitters, Transmitting and Rectifier Tubes

Remote Supervisory Control Equipment

Betatrons, Synchrotrons

Electrical Equipment for Locomotives,
Motor-Coaches, Tramcars and Trolley Buses

Published by Brown, Boveri & Company, Limited, Baden (Switzerland). Printed by Kreis & Co. AG., Basle (Switzerland)
Obtainable through A. Francke AG., Berne, and Rouge & Cie, Lausanne (Switzerland)